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Procedures for Cascade Impactor Calibration and Operation in Process Streams

Industrial Environmental Research Lab, Research Triangle Park NC

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by

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SECTION 1.0

INTRODUCTION

Inertial impactors are commonly used to determine the particle size distributions of particulate matter emitted by industrial sources. Impactors have several advantages over competing techniques: they are compact, can be inserted directly into the duct (avoiding the problem of sample loss in a probe), are fairly accurate, and produce information which is widely understood. The Process Measurements Branch (PMB) of EPA's Industrial Environmental Research Laboratory, Research Triangle Park, N. C., has been using inertial impactors to determine particle size distributions for several years, as have a number of IERL-RTP contractors. The PMB has also sponsored an evaluation of impactors to select devices that could be used under normal field conditions. During the course of these programs it became evident that no uniform approach to the field use of impactors was available.

To develop uniform procedures, a working group of IERL-RTP personnel, contractors, and independent experts met at Research Triangle Park, N. C. This procedures guide is an outgrowth of the working group's discussions. The document has several purposes. Above all, the PMB wants to ensure the comparability of data gathered by different contractors. That is, that the contractors use equipment whose characteristics are known, follow sound sampling procedures, and reduce the data using accepted and defined techniques. This document is also intended to help impactor users avoid some of the problems which others have experienced.

The procedures presented should yield quality data at most sampling sites. Situations will occur where the information gathered in this document will not be applicable and a suitable procedure will have to be worked out. Professional judgment is still the most important element in successfully determining particle size distributions and fractional efficiency.

The scope of this report includes the preliminary survey, sampling apparatus, testing procedures, data analysis, reporting requirements, and impactor calibration. The information is applicable to cascade impactors in general. Specific commercial impactors are discussed in the section titled "Commercial Impactors."

Because the state-of-the-art in impactor sampling is advancing rapidly, readers of this document are encouraged to seek additional information. For IERL-RTP contractors, the Process Measurements Branch should be contacted for updates on the guidance in this document and perhaps the resolution of some of the questions which have incomplete answers at this time.

SECTION 2.0

THE PRESURVEY

The key to performing a successful fractional efficiency evaluation is thorough planning based on a complete pretest site survey. The survey should provide adequate information at as low a cost as possible. The presurvey form presented as Appendix E is a reasonable guide to the type of information which should be noted. Some sites will require more information. As far as is possible, the information noted during the presurvey should be measured rather than obtained from plant records or personnel.

As the presurvey is generally conducted by one or two men "traveling lightly," the apparatus used during the presurvey should be as light and compact as possible. A presurvey sample train is shown in Figure 1. This system was built into a single, suitcase-sized package, and served well as a presurvey sample train. The impactor which is to be used during the main test program should normally be used during the presurvey because the suitability of substrates and adhesives must be checked out. These problems are discussed more fully in later sections.

In general, the presurvey work should be done using the techniques described in this document. Less precision is required, but the accuracy must be high enough to provide useful information in designing the test program. The decisions which must be made are summarized in Table 1.

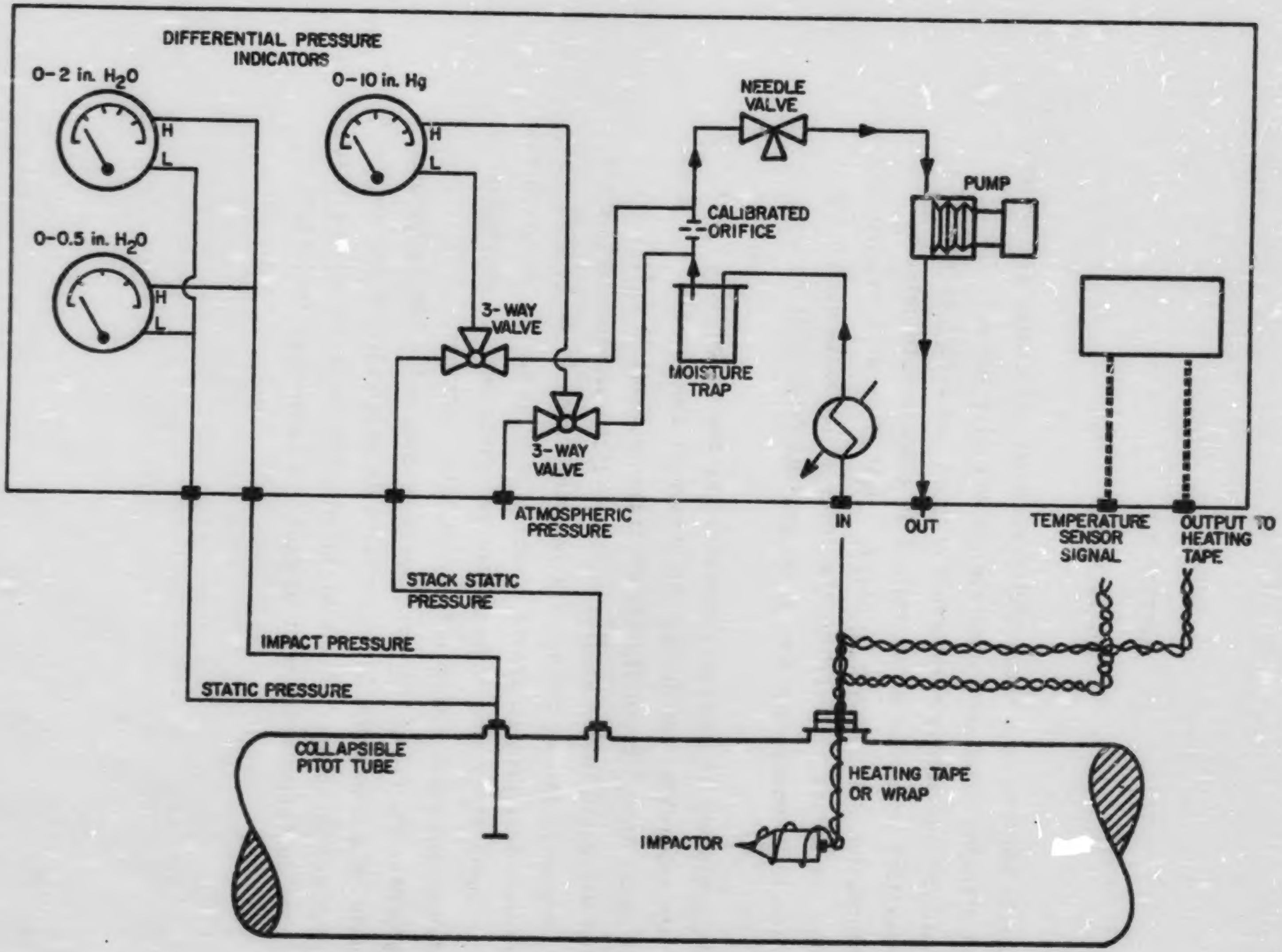

DIFFERENTIAL PRESSURE INDICATORS
0-2 in. H2O
0-0.5 in. H2O
0-10 in. Hg
H
L
H
L
H
L
NEEDLE VALVE
CALIBRATED ORIFICE
PUMP
3-WAY VALVE
3-WAY VALVE
MOISTURE TRAP
ATMOSPHERIC PRESSURE
IN
OUT
TEMPERATURE SENSOR SIGNAL
OUTPUT TO HEATING TAPE
STACK STATIC PRESSURE
IMPACT PRESSURE
STATIC PRESSURE
COLLAPSIBLE PITOT TUBE
HEATING TAPE OR WRAP
IMPACTOR

Figure 1. Presurvey sampling using an impactor.

TABLE 1. IMPACTOR DECISION MAKING

Item	Basis of Decision	Criteria
Impactor	Loading and size estimate	a. If concentration of particles smaller than 5.0 μm is less than 0.46 gm/am^3 (0.2 grain/acf), use high flow rate impactor (≈0.5 acfm). b. If concentration of particles smaller than 5.0 μm is greater than 0.46 gm/am^3 (0.2 grain/acf), use low flow rate impactor (≈0.05 acfm).
Sampling rate	Loading and gas velocity	a. Fixed, near isokinetic. b. Limit so last jet velocity does not exceed: -60 m/sec greased -35 m/sec without grease.
Nozzle	Gas velocity	a. Near isokinetic, ±10%. b. Sharp edged; minimum 1.4 mm ID.
Pre-cutter	Size and loading	If pre-cutter loading is comparable to first stage loading, use pre-cutter.
Sampling time	Loading and flow rate	a. Refer to Section 5.5. b. No stage loading greater than 10 mg.
Collection substrates	Temperature and gas composition	a. Use metallic foil or fiber substrates whenever possible. b. Use adhesive coatings whenever possible.
Number of sample points	Velocity distribution and duct configuration	a. At least two points per station. b. At least two samples per point.
Orientation of impactor	Duct size, port configuration, and size	Vertical impactor axis wherever possible.
Heating	Temperature and presence of condensible vapor	a. If flue is above 177°C, sample at process temperature. b. If flue is below 177°C, sample at 11°C above process temperature at impactor exit external heaters.
Probe	Port not accessible using normal techniques	a. Only if absolutely necessary. b. Pre-cutter on end in duct. c. Minimum length and bends possible.

SECTION 3.0

EQUIPMENT SELECTION

3.1 IMPACTOR SELECTION

The selection of the proper impactor for a particular test situation is primarily dependent upon the mass loading of the gas stream and its effect on sampling time. There are three major criteria to be met to match an impactor to a particulate stream:

1) The sampling period must be long enough to provide a reasonable averaging of transient conditions in the stack.
2) The loading on a given impactor stage must be low enough to prevent re-entrainment.
3) The sampling rate through the impactor must be low enough to prevent scouring of impacted particles by high gas velocities.

For these reasons, an impactor with a comparatively low sample rate must be used in a gas stream with a high mass loading. The low sample rate allows a longer sampling time, although in some situations it will still be undesirably short. Conversely, in a low mass loading situation such as a control device outlet, a high sample rate device must be used if a significant amount of sample is to be gathered in a reasonable amount of time.

A cascade impactor can normally yield useful information over a range of sample rates differing by a factor of 2 or 3. As high efficiency control devices cause the outlet mass loading to differ from the inlet by a factor of 10, the same impactor can seldom be used on both inlet and outlet. Both high and low flow rate impactors are usually required to determine the efficiency of particulate control devices.

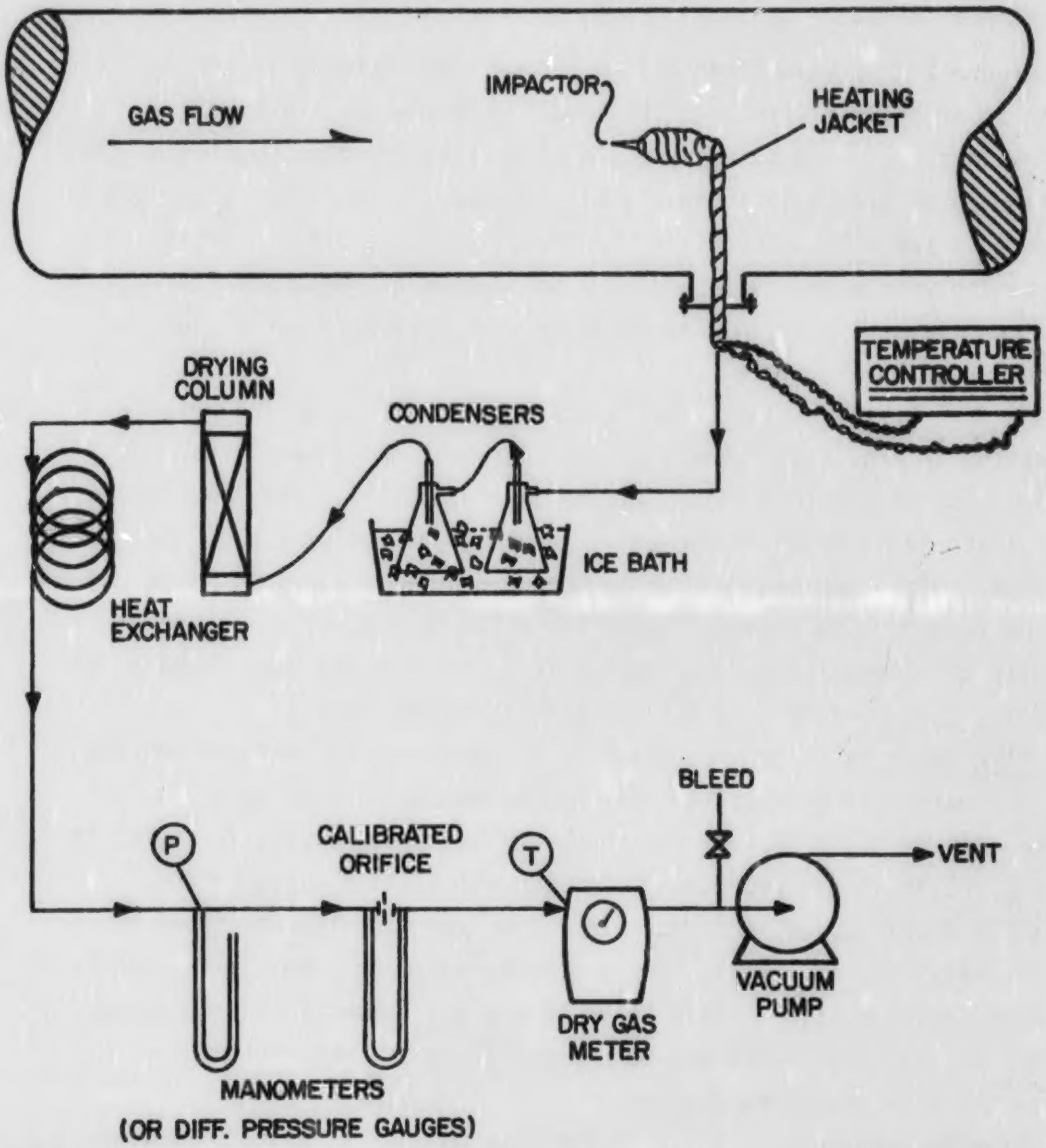
3.2 SAMPLE TRAINS

Figure 2 is a flow diagram of a typical impactor sample train. As shown, it is desirable to have the impactor inside the stack with a straight nozzle. A sampling probe leading to an impactor outside of the duct should be used only if absolutely necessary. The probe should be as short as possible and contain the fewest possible bends. It is recommended that a pre-cutter cyclone be mounted at the probe inlet to remove particles larger than approximately 10 micrometers and thus reduce losses in the probe.

Heating System -- The criteria for heating are given in Table 1. If heating is required, the entire impactor must be either wrapped in heating tape or put in a custom-fitted heating mantle. The temperature control should be based on the temperature at the outlet end of the impactor. Often the temperature is measured between the last stage and back-up filter. The impactor temperature can be controlled either manually or automatically. An automatic controller has been found to be worth its cost by releasing the operator for other tasks.

Flue Gas Conditioning -- Often it is necessary to cool and dry the flue gas before it reaches the flow measuring section, as condensation in the orifice would distort the measurement. Also, drying is useful to protect the equipment from the condensate which, in SO_2-containing gases, is likely to be sulfuric acid. The type of condenser shown is usually satisfactory. Packed-bed drying columns are commercially available. The heat exchange coil is used to bring the gas temperature to essentially ambient so that there will not be a significant temperature gradient across the flow measuring devices.

Flow Measurements -- At least two flow measuring devices are used in series. Normally, a calibrated orifice is used in conjunction with a dry gas meter, as shown. The commonly used diaphragm-type positive displacement gas meter becomes increasingly inaccurate at flow rates less than 5 percent of rated capacity. For a typical stack sampling


GAS FLOW
IMPACTOR
HEATING JACKET
TEMPERATURE CONTROLLER
DRYING COLUMN
CONDENSERS
ICE BATH
HEAT EXCHANGER
BLEED
CALIBRATED ORIFICE
P
T
VENT
VACUUM PUMP
DRY GAS METER
MANOMETERS
(OR DIFF. PRESSURE GAUGES)

Legend

Ⓟ - Pressure Measurement Point

Ⓣ - Temperature Measurement Point

Figure 2. Typical sample train with heated impactor.

gas meter this would be approximately 1.4 liters/min (0.05 cfm). Another calibrated orifice or a rotameter should then be used as the second flow meter.

Temperature Measurements -- It is necessary to know the temperature at all points where flow rate must be known. Any convenient device of known accuracy can be used to make the measurements. The in-stack measurement can easily be made at the probe end with a thermocouple. The temperature at the downstream end of the impactor is measured directly behind the final filter and is used to control the heating tape if one is used. If the heat exchanger in the train brings the gas temperature to about ambient, only one temperature reading will be necessary at the flow meters. This is usually most conveniently done at the dry gas meter, as taps are available on the meter.

Vacuum Pumps -- The vacuum pump should usually be placed at the end of the sample train. This is because vacuum pumps tend to leak and all of the flow measurements must be made upstream of any leak. The flow rate can be controlled by using an inlet side air bleed or with a recirculating bypass from the pump discharge. If a leak-free pump is available a more convenient train can be obtained by switching the pump and orifice. A standard Method 5 pump box has worked well.

Pressure Measurements -- Most of the pressure measurements are shown being made with manometers, but calibrated differential pressure meters are equally acceptable. The in-stack pressure needed is the static pressure, which is not exactly the downstream pressure of an S-type pitot tube. A true static pressure measurement should be made. It is not necessary that this be part of the impactor train, but it can be.

The pressure at the downstream end of the impactor, between the last stage and the final filter, must be known. It can be measured, but this is often inconvenient. If a flow rate pressure drop calibration is available for the impactor (without final filter), it is normally acceptable to calculate the pressure drop. Correction must be made for pressure and temperature differences between the calibration conditions and the actual conditions. The impactor is treated as an orifice, and the techniques discussed in Appendix A are used to make the corrections.

The pressure at the inlet to the metering devices must be known. In the system shown in Figure 2, the pressure is metered ahead of the calibrated orifice and the orifice pressure drop is used to calculate the pressure going into the dry gas meter. The dry gas meter pressure should be measured if there is a reason to think the procedure above was not adequate.

3.3 BALANCE REQUIREMENTS

For accurate weighing of collected material a balance with a sensitivity of at least 0.05 mg is required. This is especially true for the lower stages of the low sample rate impactors where collection of 0.3 mg or less is not uncommon. The balance must be relatively insensitive to vibration if it is to be used in the field. It is also desirable to have a balance with a weighing chamber large enough to hold the impactor substrates without folding. These capabilities are available in several electrobalances marketed in the U.S.

SECTION 4.0

SUBSTRATES

4.1 COLLECTION SUBSTRATES

For reasons which have been discussed, very accurate determinations of impactor stage catch weights are necessary. Impactor stages are generally too heavy for the tare capacity of field-usable precision balances. For this reason, the particles are captured on substrates which are lightweight and can be weighed on the balances. Generally, these substrates are made of metal foil or glass fiber.

Glass Fiber Substrates -- Glass fiber substrates are used on some commercial impactors. In addition to providing a lightweight impaction surface, glass fiber mats greatly reduce re-entrainment due to particle bounce. They are superior to greased metal substrates in very high temperature applications where the greases tend to evaporate. These substrates should be handled carefully to prevent fiber loss after weighing, and care must also be taken when using glass fiber substrates in streams containing sulfur dioxide. Recent experimentation has shown that glass fiber materials often exhibit anomalous weight gains due to sulfate uptake on the substrates. Apparently, sulfur dioxide in a gas stream can react with basic sites on most glass fiber materials and form sulfates.

There are two approaches to this problem. Substrates which will gain weight from sulfate uptake can be preconditioned in the flue gas before weighing. Two to 6 hours of exposure to the flue gas will suffice where mass loadings are high and sample times are short. In the situations where sample times are long and the collected amount of particulate matter small, it may be necessary to condition the substrates for as long as 24 hours to eliminate significant sulfate uptake and weight gains. Repeated weighings to check weight gains are necessary to confirm that the substrates can be used. Another approach is to use a fibrous substrate which shows little weight gain in a sulfur dioxide stream, if one can be found. It should be noted that the particle retention characteristics of different fiber materials vary, and the impactor calibration could change significantly if the substrate is changed.

Greased Substrates -- Grease must often be used on metal foil substrates to improve their particle retention characteristics. This is particularly important with hard, bouncy particulate. Impactor stage velocities of 60-65 m/sec have been used on greased substrates with good results, while particle bounce can become a problem at about half of that rate on ungreased substrates.

Finding a suitable grease can be difficult. The grease should not flow at operating temperature, and must be essentially non-volatile. Gas chromatographic materials such as polyethylene glycol 600 have exhibited more consistent characteristics than materials such as stopcock grease. Another class of materials which may be suitable is high vacuum greases; Apiezon L and H in particular have performed well at temperatures up to 120°C (250°F). The greased substrates must be tested as blanks in filtered process gas before they are used in the test program.

The greases are normally applied as suspensions or solutions of 10-20 percent grease in toluene or benzene. The mixture is placed on the substrate with a brush or eyedropper, baked at 400°F for 1 to 2 hours, and then desiccated for 12 to 24 hours prior to weighing. It is important to avoid an excess of grease. The desiccated, greased substrate should be tacky, but not slippery, with a film thickness about equal to the diameter of the particles which are to be captured.

Horizontal operation of the impactors with greased substrates is not recommended due to possible grease flow. Care must also be taken to ensure that grease is not blown off the substrates (which tends to occur at jet velocities greater than 60 m/sec). To some degree, grease blow-off can be avoided by using a light coating of grease on the last stages.

This is normally satisfactory from an adhesive standpoint, as the last stages usually have the lightest loading along with the highest jet velocity. Inspection of the stage catches is the best way to check on this problem.

4.2 BACK-UP FILTERS

Back-up filters are used on all impactors to collect the material that passes the last impaction stage. Binderless glass fiber filter material is normally used for this purpose in all the impactors, although the exact configuration varies.

Glass fiber back-up filters have the same problems as do glass fiber substrates. Their use in process gases containing sulfur oxides is suspect, and blanks must be run to check out the problems. Pure Teflon filters may alleviate this problem if they can be used.

SECTION 5.0

PREPARATION AND SAMPLING

5.1 SUBSTRATE PREPARATION

It is assumed that the substrates have been properly prepared and that the necessary data quality assurance steps have been taken. The substrates should be desiccated, carefully weighed, and kept in a desiccator until they are to be placed in the impactor.

5.2 IMPACTOR ORIENTATION

Whenever possible, the impactor should be oriented vertically to minimize gravitational effects such as flow of grease or movement of collected particles. Sampling situations requiring horizontal placement will occur, and extra care must be taken on such occasions not to bump the impactor against the port during entry or removal.

5.3 HEATING THE IMPACTOR

Unless a condensate is the prime aerosol being measured, all condensible vapors must be in a gaseous state until they exit from the impactor. In gas streams above 350°F, auxiliary heating is not usually required. Below 350°F the exit temperature of the impactor should be maintained at least 20°F above the process temperature if condensible vapors are present. A thermocouple-feedback temperature controller has proven useful.

When condensible vapors are present, it is sometimes necessary to heat the impactor probe to prevent any condensate formed in the probe from entering the impactor and contaminating the substrates. Water vapor is the primary problem. The probe temperature should be maintained above the vapor's dewpoint.

Whether the impactor is being heated in the duct or externally with heater tape, an allowance of 45 minutes warm-up time is recommended as a minimum to ensure that the impactor has been heated to duct or operating temperature. Thermocouple monitoring of the impactor temperature and gas temperature is recommended.

5.4 PROBES

Sampling probes leading to an impactor outside of the duct should be used only if there is no other way. They should be as short as possible and contain the fewest possible bends. It is recommended that a pre-cutter be mounted at the duct end of the probe to remove the large (>10 μm) particles and thus reduce line losses.

5.5 NOZZLE AND SAMPLING RATE SELECTION

It is preferable to use as large a nozzle diameter as possible to minimize sampling errors resulting from nozzle inlet geometry. When very small nozzles have been used with the Brink impactor, there have been some cases in which large amounts of material were retained in the nozzle or the nozzle was completely blocked. It is recommended that the inlet nozzle not be smaller than 1.5 mm, and some types of particulate material may require a larger minimum nozzle size. In some instances bent nozzles are necessary due to port location and gas direction, but these should be avoided. Particulate tends to collect in the nozzle, and it is difficult to determine the size interval in which the deposited material originated. Bent nozzles are also difficult to clean. If they cannot be avoided, bends should be as smooth as possible and of minimum angle in order to minimize the losses in the fine particle region.

For hard, "bouncy" particulate, the sampling rate must be such that the last stage velocity does not exceed 60 m/sec for greased collection surfaces or 35 m/sec for ungreased plates if no suitable substrate can be found to limit particle bounce. The flow rates above should not be considered the final word on nozzle velocity; particle bounce has been observed at nozzle velocities as low as 10 m/sec, while some particulate materials are "sticky" and will adhere at well above the maximum velocity for hard particles. The exposed substrate should be visually examined for evidence of re-entrainment and the rates adjusted accordingly. Refer to the "Quality Assurance" section of this document.

It is apparent that sample rate and nozzle size are closely coupled. The requirements for isokinetic or near-isokinetic nozzle flow sometimes impose a compromise on nozzle selection. The general order of priorities when choosing the sample rate is nozzle diameter (at least 1.4 mm), last stage jet velocity, and flow rate required for isokinetic sampling. Selection of nozzle diameter and impactor flow rate combinations for achieving near-isokinetic sampling conditions can be made from Figure 3. If a choice must be made between undersized and oversized nozzles, undersized nozzles will usually result in lower sampling errors than will oversize.

5.6 PRE-CUTTER USE

In many instances the percentage (by weight) of material with sizes larger than the first impaction stage cut point is quite high. In such cases a pre-cutter cyclone is necessary to prevent overloading on the upper impactor stages. A pre-cutter should always be used for the first test. If the weight of material collected by the pre-cutter is comparable to that on the first stage, it should be used in all subsequent runs. Cyclones can be obtained from the impactor manufacturer or can be shop made. A set of drawings of a cyclone for the Brink is included in Appendix C. The basic design can be adapted for attachment to other impactors. The use of two first impactor stages in series has also been suggested and appears to be a valid approach; however, no data are available.

5.7 SAMPLING TIME

The length of the sampling interval is dictated by mass loading and size distribution. An estimate for initial tests can be obtained from Figure 4. Two conflicting criteria complicate the choice of the sampling

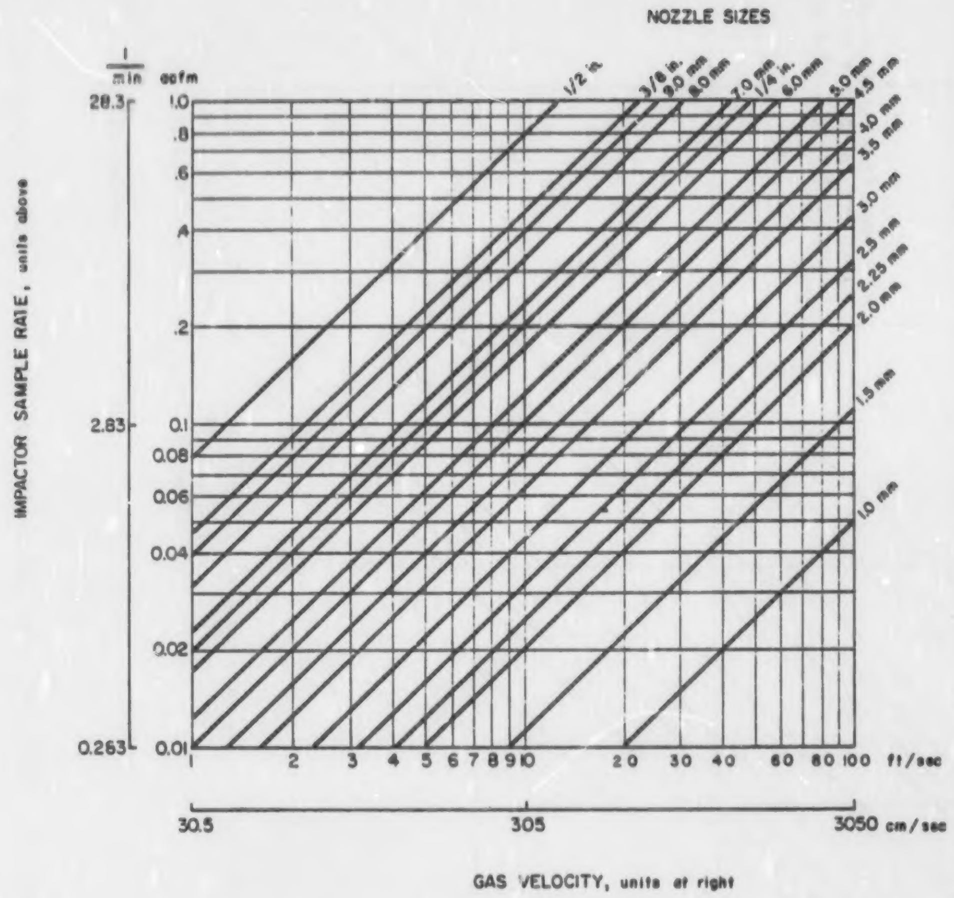
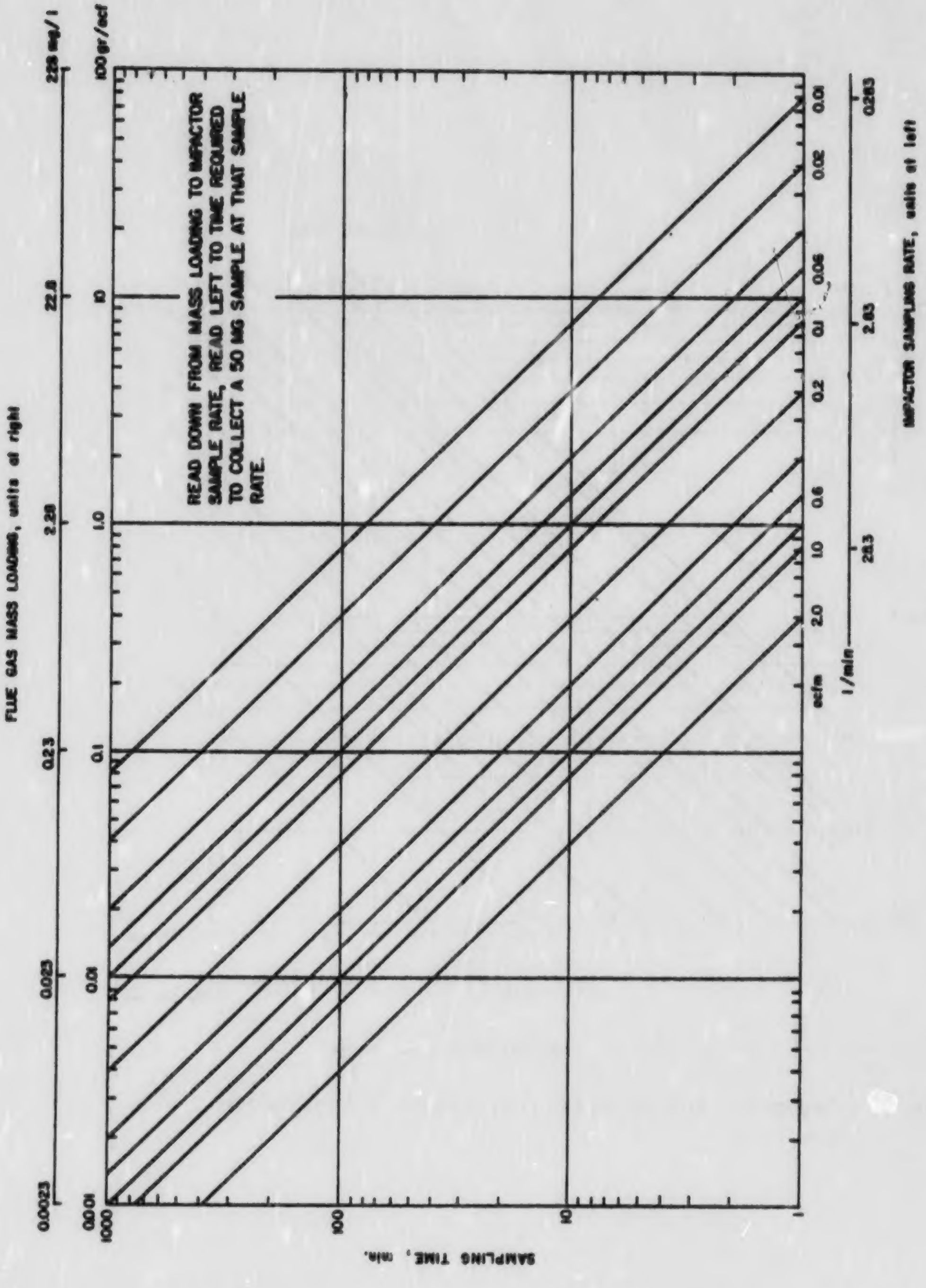


Figure 3. Nomograph for selecting nozzles for isokinetic sampling.



READ DOWN FROM MASS LOADING TO IMPACTOR SAMPLE RATE, READ LEFT TO TIME REQUIRED TO COLLECT A 50 MG SAMPLE AT THAT SAMPLE RATE.

Figure 4. Nomograph for sampling time selectio[illegible]0 mg sample).

time. It is desirable from the standpoint of minimizing weighing errors to collect several milligrams on each stage. However, most size distributions are such that the upper stages are overloaded and are re-entraining particles by the time the lower stages reach a few milligrams. A rule of thumb is that no stage should be loaded above 10 mg, but the determining factor is whether or not re-entrainment occurs. As is dicussed later, a comparison of the relative distribution determined by a long run with that from a shorter (about half as long) run can be used to check on re-entrainment due to stage overloading.

5.8 READYING THE IMPACTOR

As equipment is not always cleaned up as well as it should be, the impactor should be inspected prior to use. The nozzles must be clean, gaskets in good shape, and the interior clean. Nozzles can be cleaned with fine wire if necessary.

After inspection, the impactor should be carefully loaded with the preweighed stage substrates and assembled. Teflon-thread sealant tape or antiseize compound should be applied to the threads, especially when high temperatures (>215°C) are encountered. The thread sealant tape generally works better and causes fewer problems but probably cannot be successfully used at temperatures above 290°C.

If supplemental heating is required, a heating device and temperature monitor need to be added. A thermocouple mounted in the gas flow immediately after the final filter and inside the impactor is best for measuring the gas temperature within the impactor.

The supplemental heat can be supplied with either a heating mantle which has been made to fit the impactor or by using heating tapes. If the tapes are to be used, a heating tape of sufficient wattage is wrapped around the impactor. Glass fiber tape works well for holding the heating tape. Insulation such as asbestos tape is then wound around the impactor. Glass fiber tape is again used to hold the asbestos in place and also acts as additional insulation. The impactor can now be mounted on the appropriate probe, taken to the sampling position, and installed in the sampling system.

5.9 PRE-SAMPLE CHECKS

Impactors are prone to leak, and they must be checked for leaks at operating temperature. This can be done in several ways. The nozzle can be plugged and the impactor pressure-tested or vacuum-tested. Because impactors are basically a series of orifices, they should have a constant flow-to-pressure-drop relationship. Checking the pressure drop on various flows of filtered air will point out deviations from normal operations--both leaks (external or internal) and plugged jets.

5.10 TAKING THE SAMPLE

The impactor should be preheated for at least 45 minutes before sampling. If supplemental heat is being used, the impactor should be brought up to temperature outside the duct and then allowed some time to equilibrate after insertion. The nozzle should not point into the flow field during this phase. Without supplemental heat, the whole warm-up is conducted within the duct, again with the nozzle pointed away from the flow field. Capping the nozzle during preheat in the flue is also desirable.

A predetermined flow rate must be maintained to ensure stable cut points. Any attempt to modulate flow to provide isokinetic sampling will destroy the utility of the data by changing the cut points of the individual stages. Rapid establishment of the correct flow rate is especially important for the short sampling times typically found at the inlets to control devices.

5.11 NUMBER OF SAMPLE POINTS

As the velocity and particulate distributions in industrial ductwork are unlikely to be ideal, a large number of samples are often required for accurate particulate measurements. A velocity traverse should be run to check on the velocity distribution. At least two points within a duct should be sampled in each measurement plane, and at least two samples taken at each of these points. These are the minimum sampling efforts and are appropriate only for locations with well developed flow profiles in the absence of significant concentration stratification. If the flow profile at the station is uncertain due to duct configuration and/or the mass loading is not uniform, the number of samples may need to be increased for reliable results.

SECTION 6.0

SAMPLE RETRIEVAL AND WEIGHING

6.1 IMPACTOR CLEAN-UP

Careful disassembly of the impactor and removal of the collected particulate are essential to the success of the test program. The crucial points are to make sure that the collected material stays where it originally impacted and to remove all the particulate. After the sampling run, the impactor should be carefully removed from the duct without jarring it, removed from the probe, and allowed to cool. Disassembly can be difficult in some cases, particularly if the impactor was used at elevated temperatures.

Typically, not all of the dust which collects in an impactor collects on the substrates. Some accumulates on the interior surfaces, especially in the nozzle. By convention, all of the particulate collected upstream of a given impaction stage is assigned to that stage.

The collection of this "misdirected" particulate is often troublesome. If the dust is hard and dry, the particulate can be brushed off into the weighing container. A No.7 portrait brush or its equivalent is suggested, and care must be taken to prevent brush hairs from contaminating the sample. If the particulate is sticky or wet, some type of washdown procedure should be used. The solvent must be considerably more volatile than the particulate.

6.2 DRYING AND WEIGHING

All of the particulate must be dried to constant weight, with 2 hour checks used to establish the uniformity of the weights. Hard, non-volatile particulate is often dried in a convection oven to 212°F, desiccated until cooled to room temperature, weighed, then check-weighed. Volatile particulate will require some other technique using low temperature. Whatever the technique used, constant weight of the sample with further drying is the criteria to be met.

6.3 DATA LOGGING

Permanent records should be kept of all pertinent information. It is generally necessary to keep records in three places--in the lab with the balance (using a bound notebook), and (using either looseleaf data forms or a bound notebook) at both the inlet and outlet of the control device. Table 2 presents a fairly complete listing of the information required concerning an impactor run. Notes should be taken on any abnormalities which occur and on the apparent condition of the collected particulate.

TABLE 2. SAMPLING INFORMATION REQUIRED

- Date
- Time
- Run Code Number
- Impactor Type and Identification Number
- Operator
- Port Number/Sampling Location
- Ambient Temperature
- Ambient Pressure

- Impactor In-Stack or Out-of-Stack
- Impactor Orientation
- Number of Traverse Points
- Stack Pressure
- Stack Temperature
- Nozzle Diameter/Type
- Probe Depth, if used
- Stack Pitot Tube Delta P/Stack Gas Velocity

- Desired Impactor Flow Rate for Isokinetic Sampling
- Metering Orifice Identification Number
- Metering Orifice Delta P
- Impactor Temperature
- Scalping Cyclone in Use? Identification
- Prefilter Identification
- Postfilter Identification
- Substrate Set Identification
- Pressure Drop Across Impactor

- Test Start/End Time: Duration of Test
- Gas Meter Start/End Readings: Gas Meter Volume
- Agreement Between Meter and Orifice
- Volume of Condensible H_2O in Flue Gas
- Gas Meter Temperature

SECTION 7.0

SOME QUALITY ASSURANCE TECHNIQUES

7.1 NEED FOR A QUALITY ASSURANCE (QA) PROGRAM

The field use of cascade impactors is a difficult task. The accuracy required is more appropriate for a laboratory program than for a field test. There are many places in the operational sequence where errors can occur in spite of a conscientious effort to do a good job. A quality assurance program attempts to discover inaccuracies before they are propagated throughout the test program. It is beyond the scope of this manual to delineate a complete QA program. Such a program is being prepared and will be issued separately. The techniques presented in this section are not the only ways to ensure quality data. However, they have been used successfully in field testing with impactors.

7.2 IMPACTOR TECHNIQUES

Glass Fiber Substrates -- As has been discussed previously, glass fiber substrates are not without problems. Two potentially serious problems are SO_2 uptake on the substrate and mechanical or manual abrasion of the filter mat.

The problem of SO_2 uptake on the substrate is discussed by Smith, et al.[1] Two approaches which have been tried are: to use a substrate which does not change weight in the flue gas; or to precondition the substrate in filtered flue gas prior to weighing. Using a new glass fiber material, which does not react with the SO_2, may alter the particle retention characteristics of the impactor and change the impactor's calibration. This must be checked and the data reported. The use of preconditioned filter mats requires that the glass fiber substrates be preconditioned long enough to reduce the weight change during the expected duration of the impactor runs to 10 percent or less of the minimum stage weight. At the present time, this SO_2 reaction phenomenon is not well understood, and only rough guidelines are available. For some common glass fiber materials tested, the saturation times were on the order of 2 to 6 hours at the temperatures tested. Check with the IERL-RTP Process Measurements Branch for the latest information if glass fiber substrates are to be used.

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[1] Smith, W. B., K. M. Cushing, G. E. Lacey, and J. D. McCain, "Particulate Sizing Techniques for Control Device Evaluation," EPA-650/2-74-102a (NTIS No. PB 245184/AS), August 1975.

The applicability of the method chosen to overcome this substrate problem must be tested during the presurvey and periodically during the test runs by running blanks.

Glass fiber substrates must be handled carefully to prevent damage and possible loss of fibers. Loose surface fibers should be removed by shaking prior to weighing. After weighing, every precaution must be taken to prevent the loss of any part of the substrate. One approach which will quantify the problem of substrate abrasion is to prepare a substrate set, load the impactor, then disassemble and reweigh.

Greased Metal Substrates -- The problems which occur with the use of greased substrates are usually related to the properties of the grease. A grease which has been applied too heavily or has a low viscosity at operating temperature can be physically blown off the impactor stage. The grease could also react chemically with the flue gas or be excessively volatile at the operating temperature. Again, these phenomena must be checked during the presurvey and periodically during the test program.

Re-entrainment -- Re-entrainment is the phenomenon of an impacted particle being blown off the stage on which it was collected initially and being collected downstream. This can be caused by excessive jet velocities or by overloaded stages. The effect of re-entrainment can be serious, because only a few large particles on a stage which should collect small particles can considerably affect the size distribution.

One way to spot re-entrainment is to very carefully examine the stage catches. If, for example, a low velocity through the jets resulted in a well-defined pile of particulate and a high velocity sample gave a diffuse deposit, re-entrainment should be suspected at the high sampling rate. Microscopic examination of the lower stages and final filter for large particulate (which should have been collected upstream) is another way to check for re-entrainment.

Re-entrainment due to stage overloading can be detected by running two otherwise identical tests for two different test durations. If the two size distributions are not the same, overloading should be suspected at the higher stage loadings.

Impactor Leaks -- Two types of leaks can occur with impactors--internal or external. A flow rate versus pressure drop check or a pressure test will pick up most leaks. An internal leak, where part of the airstream is bypassing the proper flow path, will give results similar to re-entrainment. Leak checks must be made at operating temperature.

General Procedure -- A general procedure for impactor use, concentrating on quality assurance, is outlined below:

1) Preparing Impactor
    a. Wash impactor, using ultrasonic cleaner if available.
    b. Visually check cleanliness. Jets must be clear, sidewalls clean. Must be done in good lighting.
    c. Obtain preweighed substrates and assemble impactor.
2) Sampling
    a. Assemble impactor train and heat to operating temperature.
    b. Leak-check the impactor.
    c. Sample with impactor.
    d. Disassemble impactor, examine stage catches and impactor walls. Note any anomolies.
3) Substrate and Re-entrainment Checks
    a. Check during presurvey.
    b. Check substrates if flue gas composition changes significantly.

7.3 WEIGHING TECHNIQUES

Precision and Calibration -- The manufacturer's directions should be followed when operating the balance. The balance should be calibrated at least once a day. The repeatability of measurements should be checked by repeatedly weighing a substrate and a test weight.

Technique -- The assembly and disassembly of an impactor should have no effect on the substrate weights. This should be checked by weighing a set of substrates, assembling them in an impactor, then disassembling and reweighing. Any weight losses from this process should be within the repeatability of the balance (approximately 0.2 milligram for an electrobalance). Dry weight checks are made by desiccating the substrate, weighing, then desiccating again and reweighing. When the agreement is within the repeatability of the balance, dry weight has been achieved.

7.4 GENERAL NOTES

Spare Parts -- The well-equipped sampling team will travel with an adequate supply of spares. Improvisation due to an equipment failure can lead to poor quality data.

Flow Meters -- At least two flow meters should be used in series. If they do not agree, the problem should be investigated.

Pumps -- Eventually, vacuum pumps in sampling trains begin to leak. Flow meters placed upstream of the pump prevent incorrect flow measurements, due to leaking pumps though they complicate the calculations.

7.5 DATA ANALYSIS

Final Filter Data -- The fine particulate information obtained from the final filter can sometimes be misleading. It is assumed for analysis that a stage captures everything larger than its D_{50}, and captures nothing smaller. A real stage misses some large particulate. Under some conditions (including but not limited to re-entrainment), large particles will penetrate to the final filter. In this case the size distribution will be skewed toward the small particles. Microscopic examination of the final filter may provide an indication of this problem. If it occurs, the best choice in data analysis is probably to ignore the final filter on runs where this phenomenon was encountered.

Cumulative Size Data Analysis -- If a probe or a pre-cutter cyclone is used on an impactor, the probe losses and pre-cutter catches must be included in cumulative size analysis. Failure to do so will lead to an incorrect cumulative distribution.

Inspection of Data -- After the data have been collected, they should be examined for any inconsistencies or weak points. For example, the data presented as part of the "Sample Calculation," Appendix G, display two possible errors: the mass of sample caught on Stage 6, 0.008 mg, is inadequate for an accurate weight determination; and the mass caught on the final filter seems high in comparison to the mass on the other small particle stages, and re-entrainment should be suspected.

SECTION 8.0

DATA ANALYSIS

8.1 CASCADE IMPACTOR DATA ANALYSIS

The information directly available from a cascade impactor is the weight of particles caught on a stage. There are several ways to analyze and present this data as particle size distributions and fractional efficiencies across collection devices. The method which has been found most generally applicable is the "D_{50} method," described below.

8.2 D_{50} METHOD

The D_{50} method is presently used for the majority of cascade impactor data reduction. The method is fairly straightforward and can be hand-calculated, but results in a somewhat simplified picture of the real distribution.

The D_{50} of a stage is the particle diameter at which the stage achieves 50 percent efficiency; one half of the particles of that diameter are captured and one half are not. Figure 5 shows a complete set of theoretical capture efficiency curves for a modified Brink impactor. The D_{50} of Stage 4, for example, is about 1.2 μm. The calculation of stage D_{50}'s is discussed below.

The D_{50} analysis method simplifies the capture efficiency distribution by assuming that a given stage captures all of the particles with a diameter equal to or greater than the D_{50} of that stage and less than the D_{50} of the preceding stage. With this simplification, the mass collected on a given stage can be assigned to a particular diameter.

Particle-size distributions may be presented on a differential or a cumulative basis. When using the D_{50} method, either type of presentation may be easily employed.

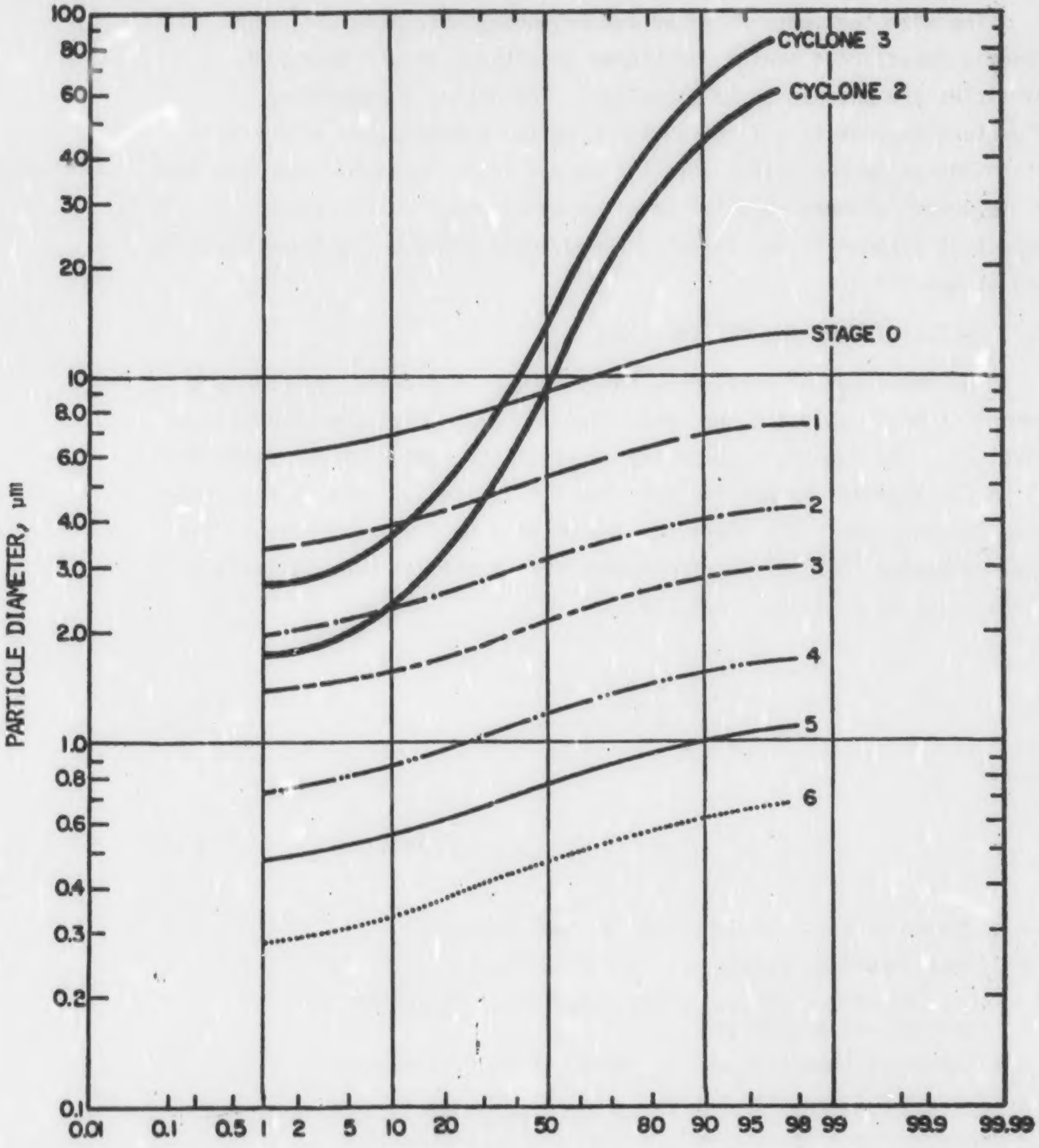

Figure 5. Stage collection efficiency for a modified Brink impactor (T=72°F, P=29.60 in. Hg, ρ=1.35 g/cm^3, flow = 0.03 acfm).

The size parameter reported can be aerodynamic diameter, aerodynamic impaction diameter, or Stokes diameter. In all cases, the particles are assumed to be spherical. The method of reporting diameters depends to a large extent upon the ultimate use of the size distribution information. For this reason it is suggested that the data be reported in three parallel sets: one set based on aerodynamic impaction diameters, one based on aerodynamic diameter, and one based on the Stokes diameter.

8.3 CALCULATION OF THEORETICAL STAGE D_{50}'S

The reduction of field data obtained with a cascade impactor can sometimes be troublesome and time consuming because of the computations involved. The equations below are based on the motion of particles for which the Reynolds number is less than 1.0. Although this is not always true for impactors, the equations are often a good approximation. The basic equation that defines the theoretical impaction behavior of a given stage of a cascade impactor is:

$$D = \left(\frac{18 \, \psi \, \mu \, D_j}{C \, \rho_p \, V_j} \right)^{1/2} \qquad (1)$$

where:

$$C = 1 + \frac{2\ell}{D} \left(1.23 + 0.41 \exp \left(\frac{-0.44 \, D}{\ell} \right) \right)^{*} \qquad (2)$$

D = diameter of particle impacting on the stage, cm

ψ = Stokes impaction parameter, dimensionless

μ = viscosity of gas at conditions immediately downstream of impactor jet(s), poise

D_j = diameter of impactor jet, cm, or width of slot impactor, cm

C = Cunningham Correction Factor

ρ_p = density of particle, g/cm^3

V_j = velocity of gas through an impactor jet, cm/sec

ℓ = mean free path of air molecule at impactor stage conditions, cm.

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*The expression for Cunningham Correction Factor is empirical; several slightly different versions are available in the literature.

As equation (1) is written, with the actual particle density and the calculated Cunningham Correction Factor, it defines the Stokes diameter. If the particles are treated as if their density, ρ_p, was 1.0, equation (1) defines the aerodynamic diameter. If the Cunningham Correction Factor is also assumed to be equal to 1.0, the aerodynamic impaction diameter is defined by equation (1).

The collection efficiency of impactor stages has been both theoretically and experimentally correlated with the impaction parameter, ψ. For the purposes of the D_{50} method, the value of ψ at 50 percent collection efficiency must be known. These values have been reported by Ranz and Wong[2], among others, and are presented below:

- for round jet impactors, $\psi_{50} = 0.145$
- for rectangular jet impactors, $\psi_{50} = 0.44$.

Other investigators have presented other values for ψ, and if an experimental value for the impactor under consideration is available, it should be used.

If the value of ψ_{50} is substituted into equation (1), it becomes an equation with which to calculate the D_{50} of a given stage of the impactor. For a round jet impactor, equation (1) becomes:

$$D_{50} = \left(\frac{2.61 \ \mu \ D_j}{C \ \rho_p \ V_j} \right)^{1/2} \qquad (3)$$

Equation (1) can be put in a form which is more convenient for field use by substituting the volumetric flow rate into the impactor for the velocity at the jet, obtaining:

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[2] Ranz, W.B. and J.B. Wong, "Impaction of Dust and Smoke Particles on Surface and Body Collectors," Ind. and Eng. Chem.: 44, No.6, 1371-81 (1952).

$$D_{50} = \left(\frac{2.05 \; \mu \; D_j^3 \; X_j \; P_j}{C \; \rho_p \; Q_s \; P_s} \right)^{1/2} \qquad (3a)$$

where: X_j = number of jets on the stage
P_j = absolute pressure immediately upstream of jet(s), mm Hg
Q_s = volumetric flow rate through impactor at stack conditions, cm^3/sec
P_s = absolute pressure in stack, mm Hg.

Similarly, the ψ_{50} for rectangular jet impactors can be substituted into equation (1), and the D_{50} equation for slot impactors obtained:

$$D_{50} = \left(\frac{3.485 \; \mu \; W_j}{C \; \rho_p \; V_j} \right)^{1/2} \qquad (4)$$

where: W_j = the slot width, cm.

Equation (4) can be converted to a volumetric flow rate basis:

$$D_{50} = \left(\frac{3.485 \; \mu \; W_h^2 L_j X_j P_j}{C \; \rho_p \; Q_s P_s} \right)^{1/2} \qquad (4a)$$

where: L_j = the slot length, cm.

One approach that can be used to further simplify the computations is to develop curves for the impactor stage cut points at one set of conditions; e.g., air at standard conditions and a particle density of 1.0. Then a suitable correction factor can be applied to these curves for the actual sampling conditions. Unfortunately, further simplifications are involved in making the correction factor simple enough to be of value. Therefore, the use of this type of approach suffers from some restrictions. Figure 5, presented earlier, shows a calibration for dry air at laboratory conditions with an assumed particle density of 1.35 g/cm^3.

All of the assumptions and calculations involved in going from equations (1) and (2) to the calibration curve can be quite awkward, particularly in cases where different types of sources are being sampled. Perhaps the best approach is to write or obtain a computer program based on the rigorous equations given initially. The program can both calculate impactor stage cut points, and compute concentrations of particles in each size range, as well as differential and cumulative size distributions. It permits more sophisticated data reduction methods to be used than would be possible by hand. Manual calculation of cut points typically takes several hours; using a computer program, several sets of data can be calculated in a few minutes. Not only is the computer faster but the possibility of computational errors is greatly reduced. Programs for both set-up calculations and data reduction are available for use on small, hand-held, programmable calculators.[3]

8.4 CALCULATION OF STAGE D_{50}'S FROM CALIBRATION DATA

Some very recent research has pointed out that the theoretical relationships presented in Equations (1) and (2) are not always accurate in commercial impactors. Work is in progress to define the full extent of the errors. Equation (3a) has been modified by the inclusion of an empirical constant, and the constant is calculated from calibration data. The new form of Equation (3a) is:

$$D_{50} = K\left(\frac{2.05\ \mu\ D_j^3\ X_j P_j}{C\ \rho_p\ Q_s\ P_s}\right)^{1/2} \qquad (5)$$

where: K = empirical constant, dimensionless, varying with impactor and stage.

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[3] Cushing, K., J. McCain, J. W. Ragland, and W. Smith, "HP-65 Programmable Pocket Calculator Applied to Air Pollution Measurement Studies-Stationary Sources," EPA-600/8-76-002, October 1976.

D_{50}'s from calibration data should be used whenever available. If calibration data are not available, the theoretical equations can be used. As before, this equation is best used as part of a computer program for the calculation of D_{50}'s. Similar calibration constants can be determined for slot impactors.

8.5 DIFFERENTIAL PARTICLE SIZE DISTRIBUTIONS -- D_{50} METHOD

The true particle size distribution of almost any particulate-containing stream outside of a laboratory is a smooth and continuous curve. As impactors have a finite number of stages, they break this continuous particle size distribution into a series of discrete piles of particulate of different size intervals. The challenge of impactor data analysis is to transform the discrete data into a good approximation of the real, continuous distribution. The D_{50} method described below is commonly used.

It is assumed for the purpose of analysis that all of the mass caught upon an impaction stage consists of material having aerodynamic diameters equal to, or greater than, the D_{50} for that stage, and less than the D_{50} for the next higher stage. For the first stage (or cyclone), it is assumed that all of the material caught has aerodynamic diameters greater than, or equal to, the D_{50} for that stage (or cyclone), but less than the maximum particle size. If the maximum particle size is not known, some arbitrary large value, say 100 μm, is used.

As the true particle size distribution is continuous, the amount of material having diameters between D and D+dD can be represented by dM. Then the integral

$$\int_{D_1}^{D_2} \frac{dM}{dD}\, dD$$

yields the total mass having diameters between D_1 and D_2.

Many cascade impactors are designed so that the relationship between successive stage D_{50}'s is logarithmic. For this reason, and to minimize graphical scaling problems, the differential particle size distributions are plotted on log-log or semi-log paper with dM/d(log D) as the ordinate and log D as the abscissa. The mass on stage "n" is designated by ΔM_n and is, in approximation, the mass of particulate with diameter between $(D_{50})_n$ and $(D_{50})_{n+1}$. The $\Delta(\log D)$ associated with ΔM_n is $\log (D_{50})_{n+1} - \log (D_{50})_n$. Using these approximations, the derivative term associated with stage "n" is:

$$dM/d(\log D)\big|_n \simeq \frac{\Delta M_n}{\Delta(\log D_{50})\big|_n} = \frac{\text{Mass on Stage "n"}}{\log(D_{50})_{n+1} - \log(D_{50})_n}$$

Plotting this approximation of dM/d (log D) versus log D results in a histogram. From such a histogram, the total mass of particles with diameters between $(D_{50})_i$ and $(D_{50})_j$ can be calculated as the sum:

$$\text{Mass} = \sum_{k=1}^{j} \frac{\Delta M_k}{\Delta(\log D_{50})\big|_k} \Delta(\log D_{50})\big|_k$$

where "k" takes on values corresponding to the discrete increments of the histogram.

If an impactor with an infinite number of stages were available, the histogram would approach a continuous function, the $\Delta(\log D_{50})$ terms would approach d(log D), and the mass between D_m and D_n could be calculated as:

$$\text{Mass} = \int_{D_m}^{D_n} \frac{dM}{d(\log D)}\, d(\log D)$$

Such an impactor does not exist, but the histogram can be plotted as a smooth curve by assigning some average of $(D_{50})_{n+1}$ and $(D_{50})_n$ to the $\Delta M/\Delta \log D_{50}|_n$ term. The geometric mean of the D_{50}'s is often used. This curve is then a continuous function approximating the actual particle size distribution. Such a curve is needed to calculate fractional efficiencies of control devices if the D_{50}'s differ for inlet and outlet measurements. The accuracy of the approximation is limited by the number of points, and by the basic inaccuracy of neglecting the non-ideal behavior of the impactors, especially overlapping collection efficiencies for adjacent stages.

To normalize the differences in mass of sample collected by various instruments, the mass on each stage is usually divided by the standard volume of the sample, yielding concentration units; i.e., $dC/d(\log D)$. A sample calculation using impactor data is presented as appendix G of this document.

8.6 CUMULATIVE PARTICLE SIZE DISTRIBUTIONS

The data may be presented on a cumulative basis by summing the mass on all the collection stages and back-up filter, and plotting the fraction of the mass below a given size versus size. This is frequently done on special log-probability paper. Semi-log paper may be preferable for distributions that are not log-normal.

Cumulative distributions are very easy to understand and present the data with clarity. For this reason, they should be presented as part of each particle sizing report. Cumulative distributions do have a couple of disadvantages when compared to differential distributions. An error in stage weight will be propagated throughout a cumulative analysis, but will be isolated by the differential approach. Also the differential method does not involve the use of total mass concentration or total size distribution from diameters of zero to infinity, and so is useful in comparing instruments with overlapping but different size fractionation ranges and different stage cut points.

When cumulative plots are used, the abscissa is normally the logarithm of the particle diameter and the ordinate is the weight percent smaller than this size. The value of the ordinate at a given $(D_{50})_k$ would be

$$\text{Weight percent smaller than } (D_{50})_k = \frac{\sum_{i=o}^{k-1} \Delta M_i}{\sum_{i=o}^{K} \Delta M_i} \times 100\%$$

where:
i = o corresponds to the filter,
i = k corresponds to the stage under study, and
i = K corresponds to the coarsest jet or cyclone

This equation requires that the stages be counted from the final filter up. There is no $(D_{50})_o$, as the "o" corresponds to the filter. $(D_{50})_1$ is the cut point of the last stage, which collects mass, ΔM_1.

An analytical curve can be fitted to the cumulative distribution obtained above, and values of dM/d(log D) obtained by differentiation of the analytical expression. In general this requires some a priori assumptions in determining the form of the expression to be used in the curve fitting process, but several independent groups have used this technique to good advantage.

SECTION 9.0

REPORTS

9.1 SIZE DISTRIBUTION

As a minimum requirement, size distribution information should be reported in cumulative size distribution plots.

The plots should be presented on log-probability paper or on semi-log paper. Plots are to be prepared based on aerodynamic diameter, physical diameter, and aerodynamic impaction diameter. The total sample weight in mg and the sample volume in Nm^3 must be included on the plot. (The term "Nm^3" means "normal cubic meters," with normal being defined as a temperature of 20°C and a pressure of 760 mg Hg.)

9.2 DATA TO BE REPORTED

The data from particulate size measurements must often be recast at a later date for a purpose other than that for which they were gathered. This can be an unsatisfactory situation unless all of the data which was collected has been reported. For this reason, all of the data which was used to calculate the final distributions should be presented in the final report, probably in the Appendix. The data presented in Table G-1 of Appendix G is almost complete. The only additional information required would be port location, type of source, appearance of particulate, and special circumstances.

SECTION 10.0

COMMERCIAL IMPACTORS

10.1 BRINK IMPACTOR

The Brink impactor is a six-stage, low sample rate, cascade impactor, suitable for measurements in high mass loading situations. Appendix C contains detailed drawings of another stage and a cyclone for the Brink. The Brink uses a single round jet on each of its stages.

Sampling Rate -- The usual sampling rates for the Brink are in the range of 0.05 - 0.2 l/min (0.02 to 0.07 acfm). The sampling rate must be low enough to prevent re-entrainment of particles from the lower stages. With hard, bouncy particulate, the last stage nozzle velocity must be less than 30-35 m/sec with ungreased substrates, and less than 65 m/sec with greased substrates.

Collection Substrates and Adhesives -- The Brink impactor collection stage is too heavy to use without a substrate. Foil cups are commonly preformed and fit into the collection cups of the Brink stages. If grease is to be used, the top stages require about 5 or 6 drops of solution while the bottom stages normally require only about 1 drop in the center of the cup. Glass fiber substrates cut to fit the collection cups have also been found satisfactory in many situations.

Back-up Filter -- The Brink back-up filter is normally made of binderless glass fiber filter material. Two 1-inch diameter disks of filter material are placed under the spring in the last stage of the impactor. The filter is protected by a Teflon O-ring and the second filter disk acts as a support.

Pre-cutter Cyclone -- A pre-cutter cyclone for the Brink is not presently commercially available. A drawing for shop construction of a cyclone is presented as Appendix C, along with details for further modifications to the impactor which have been found useful.

Sampling Train -- The Brink uses the usual type of sampling train. Orifices on the order of 0.03, 0.06, and 0.09 inches in diameter allow full coverage of its range of sampling rates at reasonable pressure drops.

Brink Clean-up -- Careful disassembly of a Brink impactor is necessary for obtaining good stage weights. If a pre-cutter cyclone has been used, all material from the nozzle to the outlet of the cyclone is included with the cyclone catch. All of this material should be brushed onto a small, tared, 2.5 x 2.5 cm aluminum foil square to be saved for weighing. Cleaning the nozzle is also important, especially if it is a small bore nozzle. All material between the cyclone outlet and the second stage nozzle is included with material collected on the first collection substrate. All appropriate walls should be brushed off, as well as around the underside of the nozzle, where as much as 30 percent of the sample has been found.

10.2 ANDERSEN IMPACTOR

The Andersen impactor is a relatively high sample rate impactor. Normal sample rates are about 15 l/min (0.5 acfm). The Andersen is a multiple jet, round hole impactor.

Sampling Rate -- The Andersen sampling rate is around 15 l/min (0.5 acfm). As with other cascade impactors, the flow rate must be low enough to prevent re-entrainment of impacted dust.

Collection Substrates and Adhesives -- Andersen substrates are obtained precut from the manufacturer. The substrates are glass fiber and of two types--one cut for the odd numbered stages, one for the even. As discussed earlier, normal Andersen substrates have a tendency to absorb SO_2 on basic sites in the substrate and, therefore, gain weight.

The Andersen requires careful assembly, as overtightening will cut the substrates or cause them to stick to the metal separator rings.

Back-up Filter -- The Andersen uses a 2-1/2 inch diameter disk placed above the final F-stage. (This F-stage is an option not normally included with the standard stack head.) The filter should be cut from binderless glass fiber filter material such as Reeve-Angel 934AH filter paper or a similar material.

Pre-cutter Cyclone -- A pre-cutter cyclone for the Andersen is available from the manufacturer. It is necessary to have a 6-inch or larger sampling port when using the pre-cutter cyclone with its nozzle.

Andersen Sampling Train -- The Andersen requires the usual type of sample train. The pumping and metering systems of the commercial Method 5, EPA mass sampling train are appropriately sized for use with the Andersen.

Care should be exercised never to allow a gas flow reversal to occur through the impactor. Material could be blown off the collection substrate onto the underside of the jet plate or the collection substrates could be disturbed. A check valve or maintenance of a very low flow while removing the impactor from the duct avoids this problem.

Andersen Clean-up -- Cleaning an Andersen impactor is difficult. Foils should be cut to hold the substrates, and each foil and substrate weighed together before and after the run. For disassembly, the foil to hold the stage 1 substrate should be laid out. Next the nozzle and entrance cone should be brushed out and onto the foil. Then the material on stage 0 should be brushed onto the foil. The stage 1 filter substrate material should then be placed on the foil and, lastly, the top of the stage 1 plate O-ring and cross piece should be brushed off. Depending on how tightly the impactor was screwed shut, some filter material may stick to the O-ring edge contacting the substrate. This should be carefully brushed onto the appropriate foil. This process is continued through the lower stages. Finally, the filter is carefully removed.

10.3 UNIVERSITY OF WASHINGTON MARK III (PILAT) IMPACTOR

The Mark III impactor is a seven-stage, high flow rate device with generally the same characteristics as the Andersen. The Mark III is a round hole, multiple jet impactor.

Sampling Rate -- The Mark III sampling rate is on the order of 0.5 acfm (15 l/min). The flow rate must be low enough to keep scouring of impacted particles to a minimum.

Collection Substrates and Adhesives -- The Mark III has often been used with supplementary foil (aluminum or stainless steel) substrates. These substrates require the use of grease for easily re-entrained particles. Enough of the grease solution is placed evenly on the substrate to adequately cover the area under the jets. The normal cautions on the use of greased substrates apply as discussed in the text.

Pre-cutter Cyclone -- A BCURA (British Coal Utilization Research Association) designed pre-cutter cyclone is available from the manufacturer.

Mark III Sampling Train -- As the Mark III is a high flow rate device, its sampling train is similar to that of the Andersen.

Mark III Clean-up -- Mark III impactor clean-up is similar to that for the Brink. Some problems have been noted with O-rings sticking rather tenaciously and care must be exercised not to dislodge the sample while trying to separate the stages.

10.4 METEOROLOGY RESEARCH, INC. (MRI) IMPACTOR

The MRI impactor is a high flow rate sampler. The body of the instrument is constructed with quick-disconnect rings which allow flexibility in configuration of the impactor and a positive gas seal between stages. The impactor uses multiple round jets in its stages.

Sampling Rate -- The sampling rate is nominally 0.5 acfm in the seven-stage configuration. Higher flow rates have been used by removing the last stage.

Collection Substrates and Adhesives -- The MRI collection disk is a self-supporting foil (316 stainless steel) which is functionally similar to the collection cup or tray and inserts used in other impactors. The collection disks are mass produced and normally are used only once and discarded.

Grease, applied as described earlier, is recommended for most applications.

Back-up Filter -- The MRI impactor has a built-in filter holder for 47 mm diameter filters. Normally, binderless glass fiber filters are used. Filter losses can be prevented by placing tared Teflon washers on both sides of the filter during the test.

MRI Sampling Train -- The MRI sampling train is similar to that of the Andersen.

MRI Clean-up -- The clean-up of the MRI impactor is similar to the Brink. The device is clamped in a vise and all of the sections and nozzles are loosened with wrenches. The wall losses are carefully brushed onto the appropriate collection disk. Care is taken not to brush contamination from the threads into the sample. A tared foil dish is used to collect the back-up filter. Any worn O-rings should be replaced and the whole unit carefully cleaned before the next test.

10.5 SIERRA MODEL 226 SOURCE CASCADE IMPACTOR

The Sierra impactor is a six-stage, high sample rate cascade impactor. The Sierra instrument uses a radial-slot design.

Sampling Rate -- The Sierra impactor has a nominal sampling rate of 0.25 acfm. The flow rate must be low enough to prevent re-entrainment of particles.

Collection Substrates and Adhesives -- Substrates for the Sierra are obtained precut from the manufacturer. These are glass fiber substrates and should be checked for weight gain. Stainless steel substrates are also available and these should normally be coated with grease as described earlier.

Back-up Filter -- The back-up filter uses a 47 mm glass fiber filter mat. It is supported by a screen from below.

Pre-cutter Cyclone -- A pre-cutter cyclone is available from the manufacturer.

Sampling Train -- The sampling train for the Sierra is similar to that of the Andersen.

Clean-up -- Clean-up of the Sierra is fairly similar to Andersen clean-up. Care should be taken to be sure the glass fiber substrates are removed intact.

SECTION 11.0

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SECTION 12.0

GLOSSARY

Aerodynamic Diameter -- The aerodynamic diameter, D_A, of a particle is the diameter of a sphere of unit density which would behave in an impactor the same as does the actual particle.

Aerodynamic Impaction Diameter, D_{AI} -- The D_{AI} is an indicator of the way a particle behaves in an inertial impactor. The D_{AI} is numerically equal to:

$$D_{AI} = D_s\sqrt{\rho_p C}$$

where:
D_s = Stokes diameter of particle
ρ_p = particle density, g/cm³
C = Cunningham Correction Factor, dimensionless.

Blank -- A blank run is one in which filtered process gas is run through the impactor to make sure that stage weight changes are due only to particulate collection. Volatile greases or SO_2 uptake on glass fiber substrates can be identified with blanks.

Bounce -- Bounce in this document refers to inadequate attractive forces between a particle and the impaction surface. If the particle does not adhere, it is said to bounce.

Condensation -- Condensation in an impactor refers to the coalescence of vapors as liquid particulate either in the gas stream or on the impactor walls.

Control -- A control is a quality assurance step similar in purpose to a blank. Usually controls are used to check on substrate preparation and weighing rather than the effects of flue gases. An extra substrate is prepared and taken out to the field, but not used. After the run is over, the control substrate is desiccated and reweighed as are the used substrates. Weight change by the control substrate indicates the magnitude of handling and weighing errors.

Cut-point -- The cut-point of an impactor stage is the particle diameter for which all particles of equal or greater diameter are captured and all particles with smaller diameters are not captured. No real impactor actually has a sharp cut-point, but the D_{50} of a stage is often called its cut-point.

D_{50} -- The D_{50} of an impactor stage is the particle diameter at which the device is 50 percent efficient. One half of the particles of that diameter are captured and one half are not. The D_{50} is normally calculated from the equation that describes the theoretical impaction behavior of impactors at 50 percent collection efficiency:

$$D_{50} = \sqrt{\frac{18\,\psi_{50}\,\mu\,D_j}{C\,\rho_p\,V_j}}$$

where:

ψ_{50} = Stokes inertial impaction parameter at 50 percent efficiency, dimensionless

μ = gas viscosity, poise

D_j = impactor jet diameter (for slot impactors, the slot width), cm

C = Cunningham Correction Factor, dimensionless

ρ_p = particle density, g/cm^3

V_j = gas velocity through impactor jet, cm/sec

This equation can be used to calculate different diameters (Stokes, aerodynamic, or aerodynamic impaction) as described below:

$D_{50,s}$ is calculated using the actual particle density and Cunningham Correction Factor,

$D_{50,A}$ is calculated using the actual Cunningham Correction Factor, but with $\rho_p = 1.0$, and

$D_{50,AI}$ is calculated with both C and $\rho_p = 1.0$.

Grease -- In impactor terminology, grease is a substance which is placed on an impactor stage or substrate to serve as an adhesive.

Isokinetic Sampling -- This is sampling with the bulk fluid velocity through the impactor nozzle equal to the velocity in the duct. This is necessary to prevent sample bias.

Physical Diameter -- See Stokes Diameter.

Pre-cutter or Pre-collector -- A collection device, often a cyclone, which is put ahead of the impactor in order to reduce the first stage loading. This is necessary in some streams because the high loading of large particulate would overload the first stage before an acceptable sample had been gathered on the last stages.

Re-entrainment -- Re-entrainment in an impactor is the phenomenon of particles which impacted on a given stage being picked up by the gas stream and moving downstream to another stage.

Stage -- A stage of an impactor is usually considered to be the accelerating jet (or plate containing multiple jets) and the surface on which the accelerated particles impact.

Stokes Diameter, D_s -- The Stokes diameter of a particle is the diameter of a sphere (with the same density as the actual particle) which would behave in an impactor the same as does the actual particle.

Substrate -- The removable, often disposable, surface on which impacted particles are collected. Substrates are characteristically light and can be weighed on a microbalance.

Wall Losses -- Wall losses are the portion of the particles in the gas stream which impact with and adhere to surfaces in the impactor other than the substrates. They must be collected and assigned to a stage.

APPENDIX A

IMPACTOR FLOW RATE MEASUREMENT

The flow rate through an impactor must be accurately measured in order to set the isokinetic sampling rate and to determine the correct impactor stage cut-points. Unfortunately, it is usually very inconvenient, and sometimes impossible, to measure the impactor flow rate at the conditions present in the impactor. The gas is normally drier, cooler, and at a lower pressure by the time the flow rate is measured; and the flow must be corrected to impactor conditions. The use of calibrated orifices and dry gas meters is discussed below.

Units

The equations presented in the Appendix are valid only if the units of the various terms are consistent. For instance, the pressure drop terms could be in units of inches H_2O or cm H_2O or something else, but all pressure drop terms must have the same units. The same is true for the other properties. Note that pressure and temperature are both absolute measurements.

Orifice Meters

The gas flow rate through a particular orifice meter is related to the pressure drop across that orifice by an equation of the form:

$$Q^2 = C\frac{\Delta P}{\rho} \qquad \text{(A-1)}$$

where:

Q = volumetric flow rate at upstream conditions

C = dimensional constant, $(\text{length})^5(\text{mass})(\text{time})^{-2}(\text{force})^{-1}$

ΔP = pressure drop across orifice

ρ = density of gas at upstream conditions.

Solving for the constant, C, in equation (A-1), one obtains:

$$C = \frac{Q^2 \rho}{\Delta P} \qquad \text{(A-2)}$$

As C is a constant at all conditions, its value can be obtained at a convenient set of conditions with a known flow rate and used later to calculate the flow rate. Equation (A-2) can be rewritten to:

$$C = \frac{Q_c^2 \rho_c}{\Delta P_c} \qquad \text{(A-2a)}$$

The subscript "c" indicates that these parameters were determined during a calibration. Density and flow rate are at upstream conditions.

Substituting equation (A-2a) into equation (A-1) yields an equation suitable for obtaining flow rates from a calibrated orifice:

$$Q_m^2 = \left[\frac{Q_c^2 \rho_c}{\Delta P_c}\right] \frac{\Delta P_m}{\rho_m} \qquad \text{(A-3)}$$

The subscript "m" denotes the parameters of the gas as it is being "measured." All are at conditions immediately upstream of the orifice. For use with impactors, the measured flow rate, Q_m, must be converted to a flow rate at stack conditions, Q_s. Assuming that the stack gas was dried as well as altered in temperature and pressure, the stack flow rate is related to the measured flow rate by:

$$Q_s(1 - F_{H_2O})\frac{P_s}{T_s} = Q_m \frac{P_m}{T_m} \qquad \text{(A-4)}$$

where:

F = water removed from flue gas, expressed as a volumetric fraction

P = absolute pressure

T = absolute temperature

The subscript "s" refers to stack conditions

At the usual conditions of relatively high temperature and low pressure which occur during stack sampling, the flue gas behaves very much like an ideal gas. The density of an ideal gas can be approximated as:

$$\rho = \frac{P(MW)}{RT} \tag{A-5}$$

where:

MW = the molecular weight of the gas

R = the universal gas constant

Equations (A-3), (A-4), and (A-5) can be combined and rearranged into a form which gives the pressure drop which must exist across the calibrated orifice, ΔP_m, to obtain the required impactor flow rate, Q_s.

$$\Delta P_m = \Delta P_c \frac{Q_s^2}{Q_c^2} (1 - F_{H_2O})^2 \left(\frac{P_s^2}{P_m P_c}\right)\left(\frac{T_m T_c}{T_s^2}\right)\left(\frac{MW_m}{MW_c}\right) \tag{A-6}$$

where:

MW_m = molecular weight of the stack gas at the orifice; normally the dry molecular weight.

MW_c = molecular weight of the calibration gas.

Dry Gas Meter

The dry gas meter, like the orifice, can only directly measure the flow rate of the gas which passes through it. This measured flow rate can be converted to the flow rate through the impactor (which is at stack condition) using the equation:

$$Q_m = Q_s \left(\frac{T_m}{T_s}\right)\left(\frac{P_s}{P_m}\right) (1 - F_{H_2O}) \qquad \text{(A-4a)}$$

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APPENDIX B

CASCADE IMPACTOR CALIBRATION GUIDELINES

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ROAP No. 21ADJ-037
Program Element No. 1AB012

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ABSTRACT

This report contains guidelines for routine calibration of cascade impactors. The basic calibration technique discussed in the report involves generating uniformly sized particles, testing individual stages, determining particle number concentrations by light scattering, and calculating efficiencies for given test parameters. Each component of the technique is discussed. The results of calibrations of three cascade impactors and comparisons with published studies are presented.

SECTION B-1

INTRODUCTION

The following report has been prepared at the request of the Particulate Technology Branch of the Environmental Protection Agency (EPA) Utilities and Industrial Power Division. The contents are intended for use as a guideline and experimental calibration of cascade impactors (C.I.) and for Air Pollution Technology (APT) internal purposes.

The calibration process is based on approximately four years of APT experience in connection with work for the EPA and other clients. In our experience, we have used University of Washington Mark III, Anderson non-viable (not the in-stack model), and APT M-1* cascade impactors and have found that calibration of these devices is necessary for accurate sizing of particles in gas streams. Variation of hole diameter and shape due to production machinery, corrosive chemical action, and particle deposition can contribute to measurement inaccuracy when using impactors. There are also discrepancies among the published studies of inertial impaction devices. Many C.I. manufacturers have not thoroughly calibrated their instruments experimentally but use the experimental results of Ranz and Wong (1952) even though Mercer and Stafford (1969) and Stern, _et al._ (1962) report much different results. Consequently, substantial uncertainties exist in the prediction of C.I. performance from past studies and manufacturer's specifications.

The basic calibration technique used by APT includes: generating uniformly sized particles, testing individual stages, determining particle number concentrations by light scattering, and calculating efficiencies for given test parameters.

The scope of this report covers the experimental technique, results of calibrations of three C.I.s, and comparisons with published studies.

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*Not available commercially.

SECTION B-2

AEROSOL GENERATION

B-2.1 CALIBRATION SYSTEM

The calibration system (Figure B-1) consists of an air-liquid atomizer, aerosol drier, charge neutralizer, particle counter, dilution air lines and appropriate metering and flow equipment. Further details on the components are included in succeeding sections.

B-2.2 PARTICLES

Monodisperse aerosols can be produced using suspensions of polystyrene latex (PSL) spheres available from Dow Chemical Corporation. Original suspensions as received are concentrated, 10 percent by weight, and can be obtained with diameters ranging from 0.087 to 2.0 microns (μm) with a standard deviation of less than 0.01 μm, and a particle density of 1.05 g/cm^3. Suspensions of PSL spheres larger than 2 μm are available; however, the standard deviations are much larger and the suspensions are more polydisperse.

Particles of 0.5 μm to 2.0 μm diameter have provided a sufficient size range for calibration of the lower four stages of both U.W. Mark III and APT C.I.'s. This is also the size range of most importance in fine particle control device evaluation. Consequently, APT has been most concerned with calibrations in this size range.

Useful suspensions of PSL can be made by diluting small quantities of the original suspension with deionized water. Any settling that occurs over a period of days can be resuspended by gentle agitation. The PSL is diluted to a concentration sufficient to minimize the occurrence of agglomerates. Dilutions of stock 10 percent solutions of PSL can be estimated from a paper by Raabe (1969); however, the amount of dilution necessary actually depends on the specific device used for spraying the

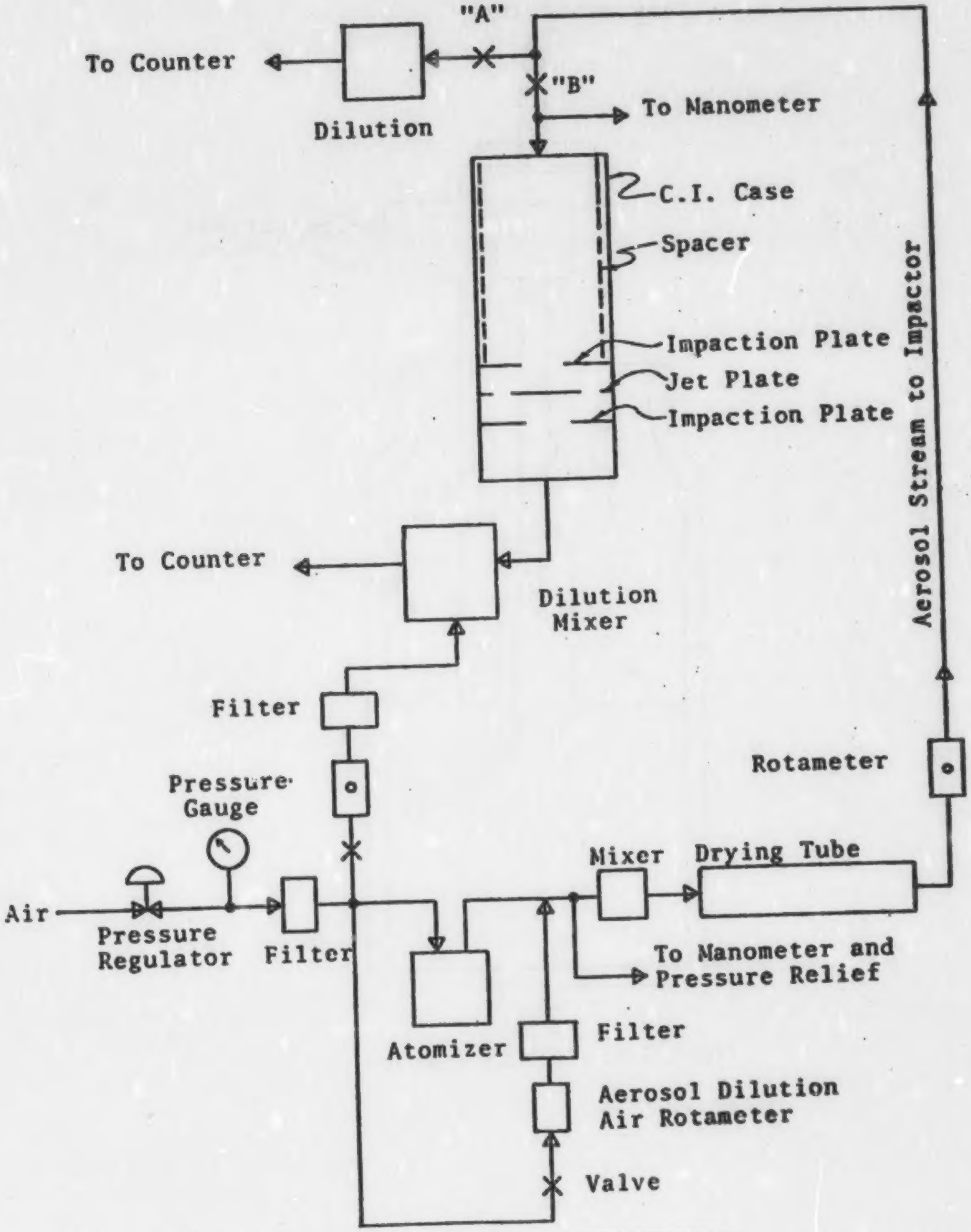
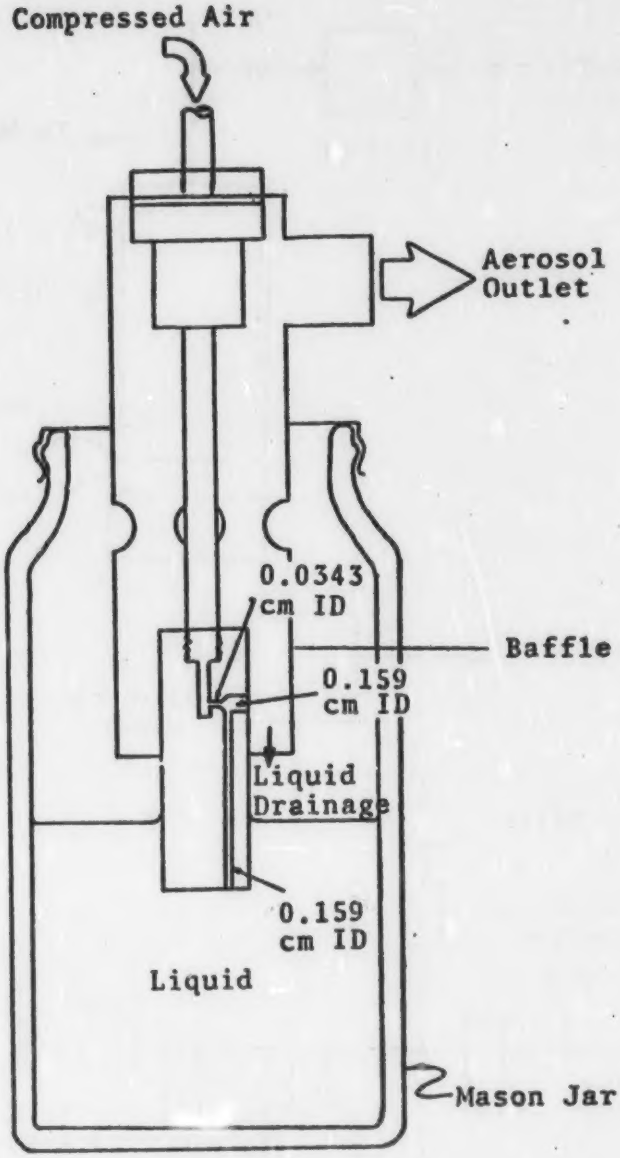

"A"
To Counter
Dilution
"B"
To Manometer
C.I. Case
Spacer
Impaction Plate
Jet Plate
Impaction Plate
Aerosol Stream to Impactor
To Counter
Dilution
Mixer
Filter
Pressure
Gauge
Rotameter
Mixer
Drying Tube
Air
Pressure
Regulator
Filter
To Manometer and
Pressure Relief
Atomizer
Filter
Aerosol Dilution
Air Rotameter
Valve

Figure B-1. Calibration apparatus



Compressed Air
Aerosol Outlet
0.0343 cm ID
Baffle
0.159 cm ID
Liquid Drainage
0.159 cm ID
Liquid
Mason Jar

Figure B-2. Collison atomizer

hydrosol. Generally, the necessary dilution must be determined experimentally by observing collected samples of dried aerosol with a microscope. If doubles run more than 2 to 5 percent, the suspension should be further diluted.

Concentrations of 0.004 percent to 0.03 percent (by weight) for particles of 0.5 to 2.0 μm were found to be compatible with the spray device in Figure B-2.

B-2.3 PARTICLE GENERATOR

Drops containing PSL particles are produced from suspensions with a Collison type atomizer as shown in Figure B-2. The operating range of this device is normally 170 to 350 kPa (10 to 50 psig) and operating characteristics vary with each device. May (1973) has tabulated some of the characteristics of a 3 jet model Collison atomizer (Table B-1).

Number concentrations and drop size distributions produced by the atomizer are consistent for a given operating pressure, provided that the liquid level and concentration are maintained. Evaporation losses will cause an increase in the particle concentration and the number of agglomerates. This has not been a problem for test periods up to 3 hours in duration. For longer periods it would be necessary to periodically sample and test for agglomerates, and further dilute the PSL solution as necessary.

Drops leaving the atomizer are mixed with dry, filtered air (approximately 45 l/min). This minimizes agglomeration of wet particles, dilutes the aerosol to a given number concentration, and aids in drying out the wet particles.

The aerosol is dried by passing it through a 1.2 m (4 ft) section of a 3.8 cm (1.5 in) diameter glass tube mounted horizontally with a layer of silica gel (~1.5 cm deep) spread evenly along the bottom. Three "Staticmaster 2U500" 500 μc, Po^{210} alpha emitters (available from Nuclear Products Company) are situated end to end at the "dry" end of the glass tube to reduce the excess charge on particles to the minimum level described by Boltzman's law. No license is required to use these units.

TABLE B-1. OPERATING CHARACTERISTICS OF A 3 JET COLLISON ATOMIZER

Air Pressure	kPa	103	138	172	207	276	345
Free air consumption	l/min	6.1	7.1	8.2	9.4	11.4	13.6
Water loss, drop + vapor	ml/hr	7.8	8.7	9.5	10.4	12.0	14.0
Approx. water vapor output	ml/hr	4.6	5.4	6.2	7.1	8.6	10.2
Approx. drop output	ml/hr	3.2	3.3	3.3	3.3	3.4	3.8
Total water conc. in outlet port	g/m^3	21.3	20.4	19.3	18.4	17.5	17.2
Droplet conc. in outlet port	g/m^3	8.7	7.7	6.7	5.9	5.0	4.7

SECTION B-3

PARTICLE CONCENTRATION MEASUREMENT

B-3.1 PARTICLE COUNTER

Particle number concentrations are determined using a Climet Cl 205 Particle Analyzer. Other commercially available instruments utilizing similar "electro-optical" techniques are also satisfactory. The Climet device has the capability of counting all particles with diameters greater than a preset value (0.3, 0.5, 1, 3, 5, or 10 μm). Further discrimination can be achieved by using a potentiometer to provide a continuous selection over the range from 0.3 to 10 μm.

B-3.2 COUNTING PROCEDURE

The particle counter is used within a selected band of particle diameters, centered about the known PSL diameter. This reduces the effect of spurious counts resulting from fine impurities and agglomerates. The particle count for the larger diameter setting may be subtracted from that for the smaller diameter setting to determine the number concentration of particles within a desired size interval. It has been our experience that spurious counts may still be a problem within the size ranges available on the Cl 205. Therefore, it is recommended that a potentiometer be used to zero in as closely as possible to the actual PSL particle size.

The maximum count allowed for the Cl 205 is 3.5 x $10^7/m^3$ ($10^6/ft^3$). The sample must be taken from a stream at or very near ambient pressure. The Cl 205 requires a flow rate of 7 ℓ/min.

The sampling inlet arrangement is illustrated in Figure B-3. A 4 mm OD tube is used for the inlet to the particle counter. It is inserted a few millimeters into the sampling tube (10 to 15 mm ID). Thus, a sampling

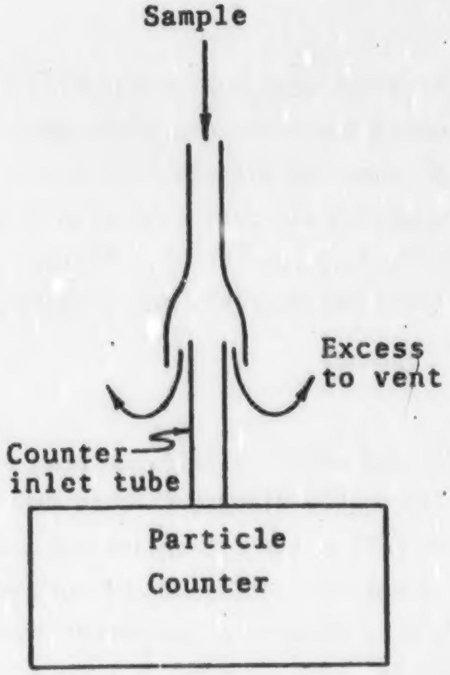

Sample
Excess to vent
Counter inlet tube
Particle Counter

Figure B-3. Sampling system Arrangement

flow rate larger than 7 l/min is handled by letting the excess flow exit through the annular space between the tubes. This arrangement also ensures that the inlet flow to the particle counter is at atmospheric pressure. Tygon tubing and variable pinch clamps have been used satisfactorily as throttles to control the sampling flow rate and the flow rate through the impactor. They are shown as "A" and "B" in Figure B-1.

SECTION B-4

CALIBRATION PROCEDURE

B-4.1 GENERAL CONSIDERATIONS

There are alternative approaches to calibration which offer advantages and disadvantages in terms of the amount of information gained versus the time, effort, convenience, and simplicity. Before going into the details of the calibration procedure, a few important principles will be pointed out.

Determining the stage cut diameter is the primary objective of the calibration. The computation of particle size distribution can be based on stage cut diameters with good accuracy, so long as particle bouncing on the upper (larger cut diameter) stages is prevented. Therefore, the calibration should concentrate on the particle size range in the vicinity of the stage cut diameter. For all stages, the inertial impaction parameter (defined in equation B-1) at the stage cut point has a value of approximately 0.2. Therefore, it is suggested that the calibration of any stage should cover an impaction parameter range of 0.1 to 0.3. These values are for round jet impactors.

The present procedure calibrates one impaction stage at a time because it is simpler, in determining collection efficiencies from inlet and outlet particle concentrations, not to have to account for the contributions of two or more stages in series. Interference from the upstream plate, noted by Willeke and McFeters (1975), has been observed mainly for large particles in rectangular jets. Very little effect has been noted for small cut diameter stages with round jets. In calibrating single stages, however, it is necessary to ensure that the flow pattern is very nearly the same as in actual operation. Therefore, the present procedure requires an impingement plate to be placed upstream of the jet plate being calibrated.

This arrangement is shown in Figure B-1. Further experiments are presently underway to determine the influence of one or more upstream impactor stages.

Some question has arisen as to expansion effects on hole diameter under hot and cold flow conditions. The most practical method for resolving this problem is to calibrate the impactor at various temperatures.

B-4.2 DEFINITIONS

The inertial impaction parameter is defined as follows:

$$K_p = \frac{D^2 \, C \, \rho_p \, V_j}{9 \, \mu \, D_j} = \frac{D_{AI}^2 \, V_j}{9 \, \mu \, D_j} \times 10^{-8} \qquad \text{(B-1)}$$

where K_p = inertial impaction parameter, dimensionless*

C = Cunningham slip correction factor =

$$1 + \frac{2\ell}{D} \, [1.257 + 0.40 \exp(-1.10 \, D/2\ell)]$$

ℓ = mean free path of gas molecules, cm

D_{AI} = aerodynamic particle diameter, μmA

ρ_p = particle density, g/cm³

V_j = gas (particle) velocity through jet, cm/sec

μ = gas viscosity, poise, g/cm-sec

D_j = jet diameter, cm

μmA = μm $(\mathrm{g/cm^3})^{1/2}$

Aerodynamic diameter is defined as:

$$D_{AI} = D_s \, (C \, \rho_p)^{1/2} \, 10^4, \ \mu\mathrm{mA} \qquad \text{(B-2)}$$

---

*The inertial impaction parameter as defined in this appendix, K_p, is defined such that it has twice the value of the ψ defined in the body of the report. The difference arises from an arbitrary decision in the derivation of equation (B-1); the 9 in the denominator of equation (B-1) rather than an 18 is another consequence.

For the case where the stage is 50 percent efficient (i.e., the cut point) following parameters are substituted into equation (B-1).

$K_{P_{50}}$ = inertial impaction cut parameter; K_p at 50% efficiency
D_{50} = cut diameter or diameter (D) at which stage is 50% efficient
$D_{AI,50}$ = aerodynamic cut diameter

Thus,

$$K_{P_{50}} = \frac{D_{50}^2 \; C \; \rho_p \; V}{9 \; \mu \; D_j} = \frac{D_{AI,50}^2 \; V}{9 \; \mu \; D_j} \times 10^{-8} \qquad \text{(B-3)}$$

B-4.3 PARTICLE SIZE SELECTION

B-4.3.1 Obtain Theoretical Impactor Curves

Theoretical curves of cut diameter versus flow rate through the impactor are usually provided by the manufacturers of commercially available cascade impactors. These curves are generally based on some value of the inertial impaction parameter at the cut point (i.e., $K_{P_{50}}$ in equation (B-3)). If these curves are not available, they may be approximated using equation (B-3) written in the form:

$$D_{AI,50} = \frac{0.135 \; \pi \; \mu \; D_j^3 \; X_j \; K_{P50}}{Q_s(10^{-8})} \qquad \text{(B-4)}$$

where Q_s = total flow rate, l/min
X_j = number of jets or holes in an impaction stage

A good approximation may be obtained using $K_{P_{50}} \approx 0.2$.

Curves of the aerodynamic cut diameter versus flow rate for the seven-stage APT M-1 cascade impactor are presented in Figure B-4 and are based on $K_{P_{50}} = 0.2$.

B-4.3.2 Determine PSL Particle Diameters and Flow Rates for the Calibration

The PSL particle diameters available commercially are listed in Table B-2. The standard deviation is very large for particles greater than about 2 μm. Therefore, 2 μm is the largest size PSL particle suitable for use as a standard aerosol for calibration.

The aerodynamic diameter corresponding to a 2.02 μm diameter PSL particle can be calculated from equation (B-2) and is equal to 2.13 μmA, a minimum flow rate of 20 l/min is required for Stage 4. Therefore, 20 l/min is a convenient flow rate to use. From Figure B-4 it can be seen that a flow rate of 20 l/min corresponds to aerodynamic cut diameters of about 1.1, 0.6, and 0.4 μmA, for Stages 5, 6, and 7 respectively. The most suitable PSL particle diameters for each stage can be obtained from Table B-2. Figure B-5 is a convenient plot (from Calvert et al. (1972)) for the conversion between aerodynamic and physical diameters.

For example, assume that 0.5 μm diameter PSL particles are being used to calibrate Stage 7 of the APT M-1 impactor. From Figure B-5, the corresponding aerodynamic diameter for a particle density of 1.05 g/cm^3 is about 0.58 μmA. The flow rate required for a cut diameter of 0.58 μmA is obtained from Figure B-4 and equals about 8.5 l/min. This cut diameter is for $K_{P_{50}} = 0.2$. Using equation (B-2), the flow rates required for $K_{P_{50}} = 0.1$ and $K_{P_{50}} = 0.3$ can be calculated to be 4.3 l/min and 12.7 l/min respectively.

TABLE B-2. AVAILABLE PSL PARTICLE DIAMETERS
(Source: Dow Chemical Company)

Avg. Diam. In Microns	One Std. Dev. In Microns	Material	Density g/ml
0.087	0.0046	Styrene-Butadiene	= 1.05 unless otherwise noted
0.091	0.0058	Polystyrene	
0.109	0.0027	Polystyrene	
0.176	0.0023	Polystyrene	
0.234	0.0026	Polystyrene	
0.255	0.0022	Styrene-Butadiene	
0.312	0.0022	Polystyrene	
0.357	0.0056	Polystyrene	
0.364	0.0024	Styrene-Butadiene	
0.460	0.0048	Polystyrene	
0.481	0.0018	Polystyrene	
0.500	0.0027	Polystyrene	
0.527	0.0125	Styrene-Butadiene	0.99
0.600	0.0030	Polystyrene	
0.721	0.0057	Polystyrene	
0.760	0.0046	Polystyrene	
0.794	0.0044	Polystyrene	
0.801	0.0035	Polystyrene	
0.804	0.0048	Polystyrene	
0.807	0.0056	Polystyrene	
0.822	0.0043	Polystyrene	
1.011	0.0054	Polystyrene	
1.099	0.0059	Polystyrene	
1.101	0.0055	Polystyrene	
2.020	0.0135	Polyvinyltoluene	1.027
5.7	1.5	Styrene Divinylbenzene	
15.8	5.8	Polystyrene	

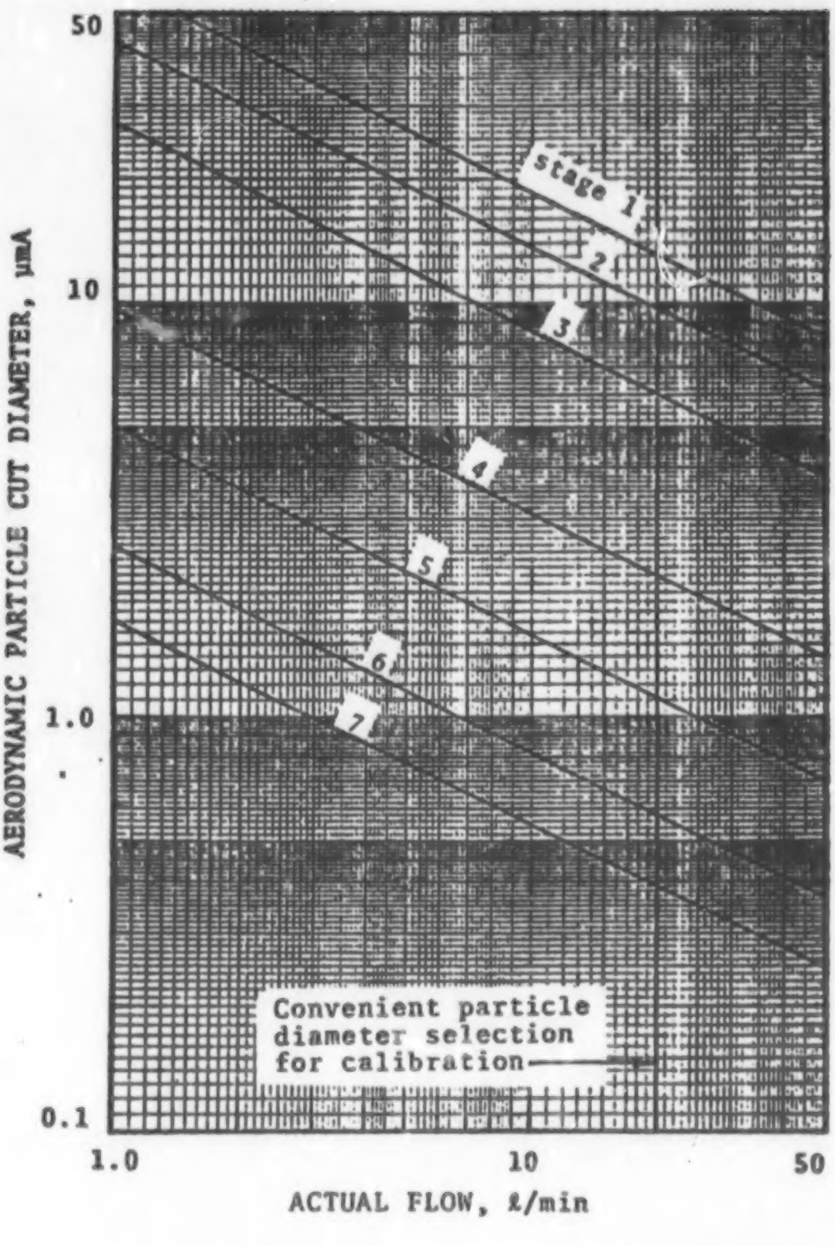


Figure B-4. Aerodynamic cut diameter vs. impactor flow for A.P.T. M-1 cascade impactor.

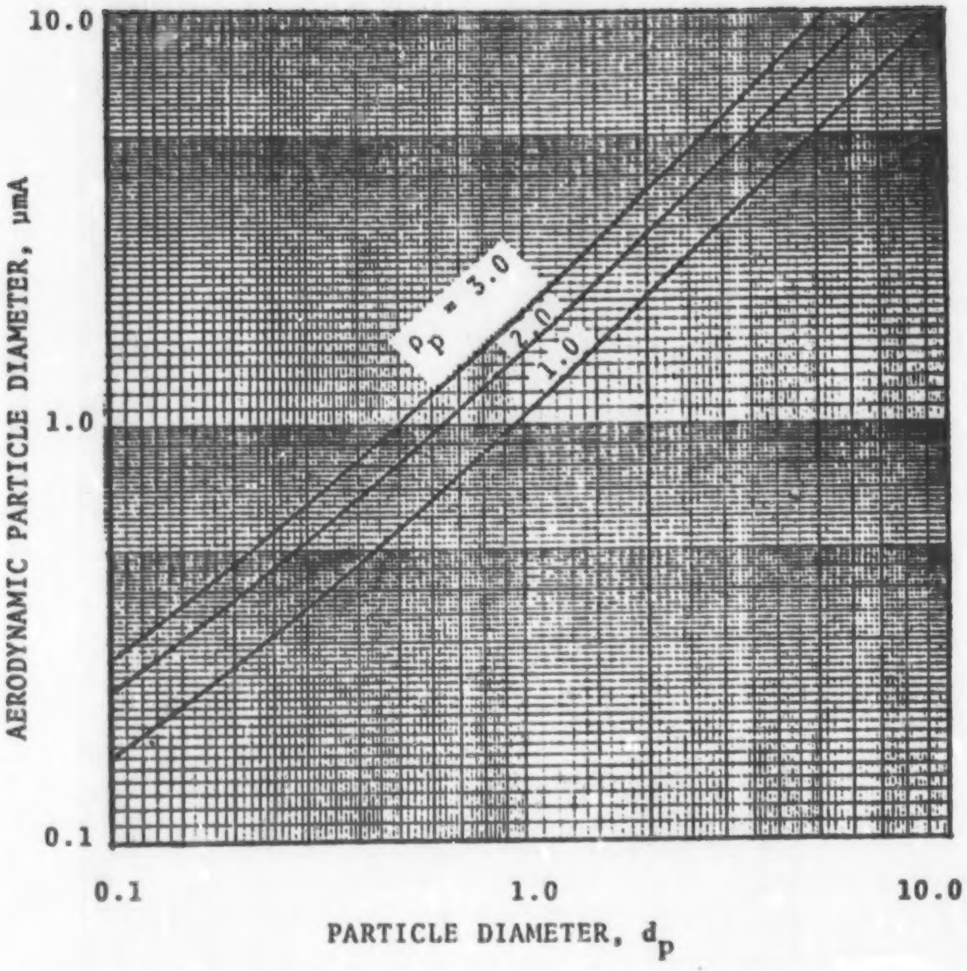


Figure B-5. Aerodynamic diameter vs. diameter for various densities.

B-4.4 IMPACTOR PREPARATION

B-4.4.1 Inspect and Clean Impaction Plates

Inspect the jet orifices with a microscope to ensure that they are clean and round. If necessary, clear the orifices with a wire. Clean the jet and impaction plates in an ultrasonic bath with a detergent solution. Rinse first with distilled water, then with acetone. Reinspect the jet orifices and repeat cleaning if necessary. Some jets may be irregularly shaped because of poor manufacturing. Such jets may be calibrated as they are, or returned to the manufacturer.

B-4.4.2 Grease Impaction Plates

Apply grease to the impaction plates or foil substrates in the same manner as for normal laboratory or field use of the cascade impactor. APT uses Dow Corning high vacuum silicone grease or equivalent. If fibrous substrates are being evaluated, they should not be greased.

Because the particulate concentration will be counted upstream and downstream of the impaction plate, it is not necessary to perform a gravimetric analysis of the substrate and collected particulate. However, a gravimetric analysis is suggested as a check on the particulate mass balance of the system. If a mass balance check is being conducted, it is necessary to record the flow rate and time for the duration of the test. This will enable the prediction of the total particulate mass entering and leaving the system. The difference can then be compared to the mass collected on the impaction plate.

B-4.4.3 Assemble Impaction Stage

Place the impaction stage in the calibration tube as shown in Figure B-1. To provide the proper flow pattern, place an impaction plate upstream and downstream of the jet plate. The regular cascade impactor casing can be used as the calibration tube if tubular spacers are made to provide proper alignment and seals between the components. Alternatively a special calibration tube could be constructed.

B-4.5 MEASURE STAGE PRESSURE DROP

B-4.5.1 Measure Pressure Drop as a Function of Flow Rate

This provides data which enable the use of the stage as an orifice flow meter during the calibration. It also provides a means for checking the jet orifice size by comparing the pressure drop/flow rate data against data for a known jet plate. This is a useful check both in the laboratory and in the field.

Measure the flow rate with a calibrated rotameter. The rotameter should be calibrated against a wet test meter every six months or whenever it is in disagreement with secondary flow measurements (for example, the pressure drop measurements).

Measure the pressure drop across the impaction stage with an open end manometer attached to the upstream side of the impactor casing and downstream of throttle valve "B" in Figure B-1.

B-4.5.2 Plot Pressure Drop Against Flow Rate

Pressure drop is conveniently plotted against flow rate on log-log paper to give a straight line relationship. A typical impaction plate will have a pressure drop directly proportional to the square of the flow rate. For example, Stage 5 of a U.W. M-III impactor has a flow resistance which follows the relationship:

$$\Delta P \text{ (cm W.C.)} = 0.2\,(Q_s)^2 \qquad \text{(B-5)}$$

B-4.6 PARTICLE PENETRATION

B-4.6.1 Select Dilution Air Flow Rate

Select the dilution air flow rate necessary to dry the aerosol and also to bring it to the desired particle concentration range for counting. The general flow rate range is given in Section B-2 above.

B-4.6.2 Start Dilution Flow to the Dryer

After checking the system to be sure that valves are open and closed as required to allow the flow to pass through the impactor stage, start the dilution air flow to the aerosol dryer. Use the pressure regulator, throttle valves, and rotameter to adjust the flow rate.

B-4.6.3 Load and Start Atomizer

Load the atomizer with about 500 ml of PSL suspension diluted from roughly 0.5 ml of concentrated latex. Start the atomizer, controlling the flow rate by adjusting the pressure regulator and the pressure gage. The atomizer flow resistance should be checked periodically by passing air from a dry atomizer (no liquid present) through a flow meter to detect any nozzle plugging.

B-4.6.4 Adjust Flow Rate

Adjust the upstream sampling throttle "A" so that the pressure drop across the impactor is proper for the desired impactor flow rate, "Q_s". Keep throttle "B" open as much as possible. Set the outlet dilution air flow rate to provide more than 7 l/min total flow into the particle counter.

When flow or concentration changes are made, approximately five system volume change time intervals should elapse before any data are taken to allow steady state conditions to be reached. This can take several minutes for some low flow rate impactors (e.g., Brink impactors).

B-4.6.5 Measure Particle Concentration

Warm up the circuits of the particle counter for several minutes as recommended by the manufacturer. Particle counting should be done on the potentiometer setting as close as possible to the PSL particle diameter. To check the extent of agglomeration, it is helpful to use the next highest channel also. In general, record counts in all three channels, below, above, and at the PSL diameter.

The data recorded should include the following:

a. Stage identification
b. Particle identification parameters
c. Particle suspension (as used) specifications
d. Barometric pressure
e. All rotameter readings
f. All pressure readings
g. Air temperature at impactor inlet
h. Particle counts on 2 or 3 channels for inlet and outlet of impactor.

Make counts over the complete range of air flow rate going both up and down. Plot the data obtained in the simplest meaningful form so they can be checked for consistency. Computation methods, as discussed in Section B-5, are used to obtain particle penetration. A plot of penetration versus impactor pressure drop requires the least computation and serves the purpose. Inspect the plot for scatter of data and compare with the anticipated curve. If it is unsatisfactory, make any worthwhile modifications and repeat the run.

At this point it is advisable to inspect the impaction plate by eye and with a microscope. A visual examination can show whether the plate is overloaded. Microscopic examination of light deposits enables the detection of spurious particles.

Continue taking and plotting data until satisfied that reproducible data have been obtained.

SECTION B-5

RESULTS

B-5.1 DATA REDUCTION

B-5.1.1 Compute Inlet and Outlet Particle Concentrations

Compute inlet and outlet particle concentrations by subtracting the concentration measured on the high diameter channel from that measured on the lower channel. For example, if counting 0.5 μm diameter particles, subtract the concentration counted on the 1.0 μm channel from that counted on the 0.3 μm channel (see sample calculation, Section B-8.4). The net concentration should be equal to the concentration measured at the potentiometer setting closest to the PSL diameter. If this is not the case, spurious counts may be a problem, and the concentration measured closest to the PSL diameter should be used. If possible, use the potentiometer to narrow the band around the PSL diameter until no spurious counts are detected.

B-5.1.2 Adjust Outlet Concentrations

Adjust outlet concentrations to the same (undiluted) basis as the inlet concentration in cases where dilution of the outlet sample has been necessary.

B-5.1.3 Compute Particle Penetration

Compute particle penetration, Pt, as the ratio of outlet to inlet particle concentrations (undiluted basis). Particle collection efficiency in fractional form is (1-Pt), and in percentage it is 100 times the fractional efficiency.

B-5.1.4 Obtain the Impactor Gas Flow Rate

Obtain the impactor gas flow rate from the previously determined plot of pressure drop versus flow rate, using the measured pressure drop for each penetration data pair.

B-5.1.5 Compute Inertial Impaction Parameter

Compute inertial impaction parameter from the measured air flow rate and properties, particle properties, jet hole size and number of holes by means of equation B-1. Jet velocity may be computed from the hole diameter, number of holes, and air flow rate.

B-5.1.6 Results

Results can be plotted in several ways, depending on their desired use. For checking the data quickly during the calibration procedure, a plot of penetration versus impactor pressure drop is convenient. A plot of efficiency versus impaction parameter is more useful for interpretative purposes.

B-5.2 TYPICAL DATA

B-5.2.1 Particle Collection Efficiency Data Points

Particle collection efficiency data points for a single calibration run on State 7 from an APT M-1 impactor are plotted against impaction parameter in Figure B-6. The curve in Figure B-6 represents the composite of data points for several Stage 7 runs.

B-5.2.2 Data for Stage 5 Plates

Data for four separate U.W. M-III Stage 5 plates are plotted in Figure B-7.

B-5.2.3 APT M-1, U.W. M-III, and Andersen Calibrations

Figures B-8 through B-10 show the results of calibrations of the APT M-1, U.W. M-III, and Andersen non-viable cascade impactors in terms of collection efficiency versus impaction parameter for each stage. The curves represent the composites of several runs on different plates. Data points are omitted for clarity.

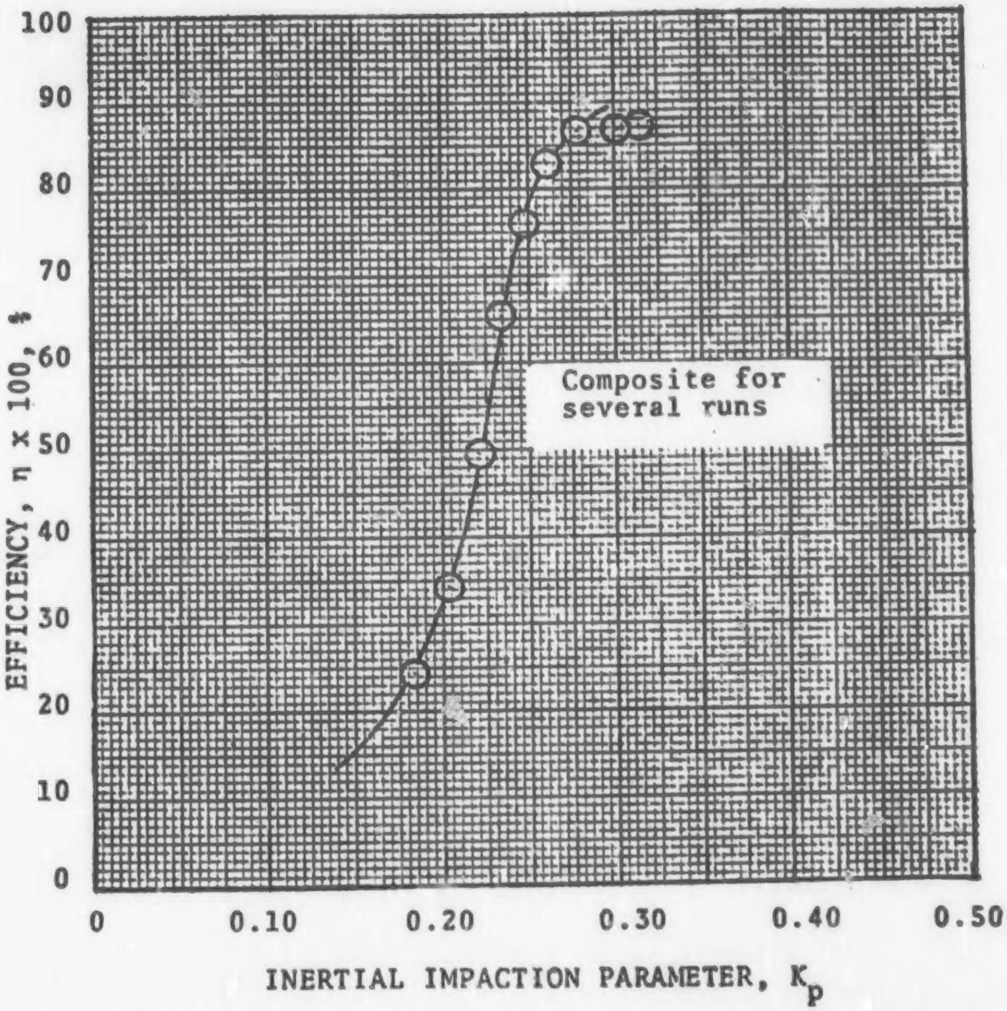


Figure B-6. Efficiency vs. inertial impaction parameter for A.P.T. M-1 cascade impactor, stage 7.

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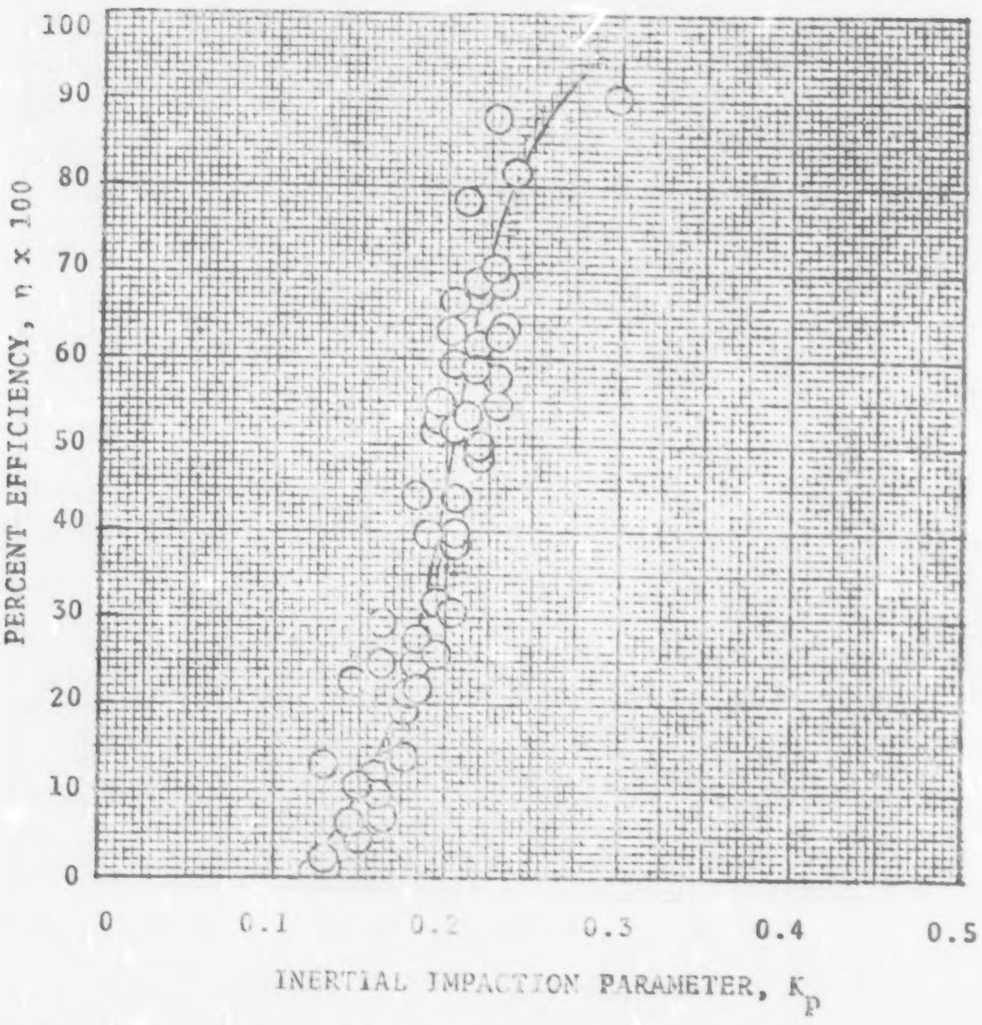

Figure B-7. Efficiency vs. inertial impaction parameter, data from 4 separate U.W. Mark III cascade impactors, stage 5.

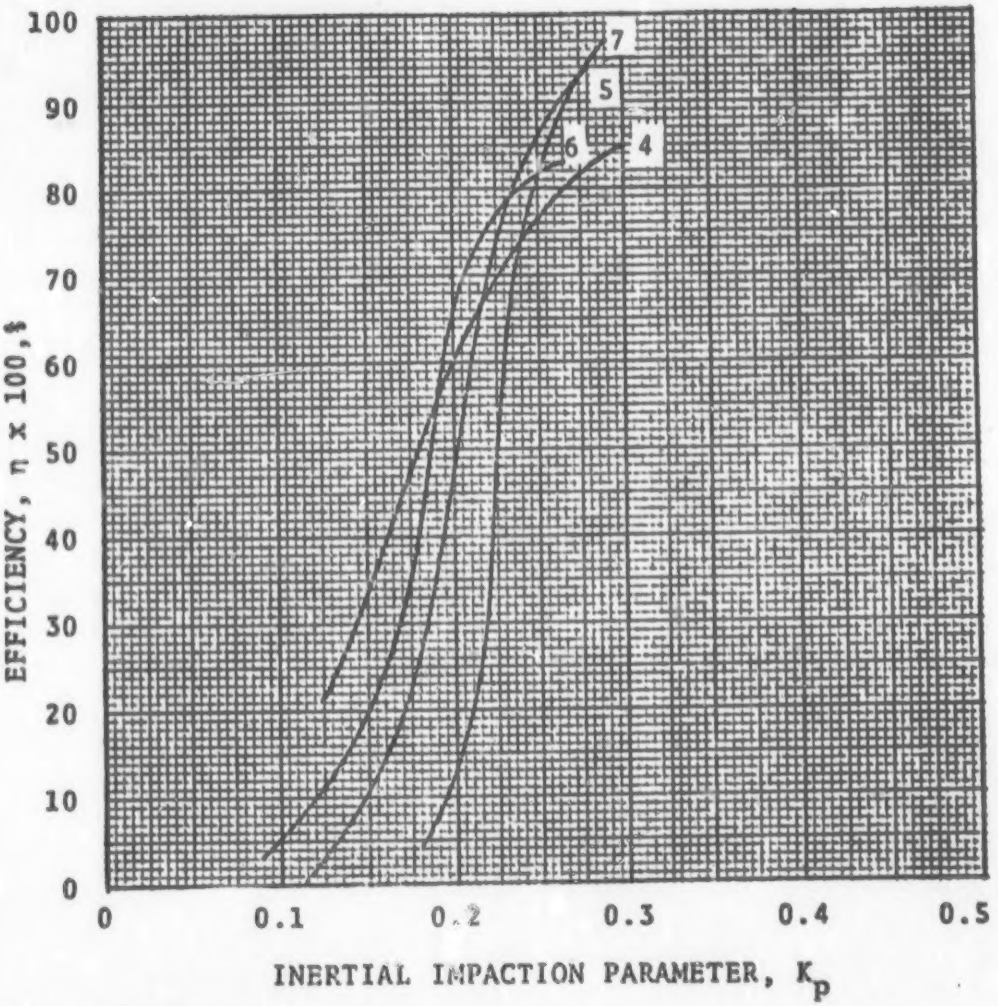

Figure B-8. Efficiency vs. inertial impaction parameter for U.W. Mark III cascade impactor, stages 4-7.

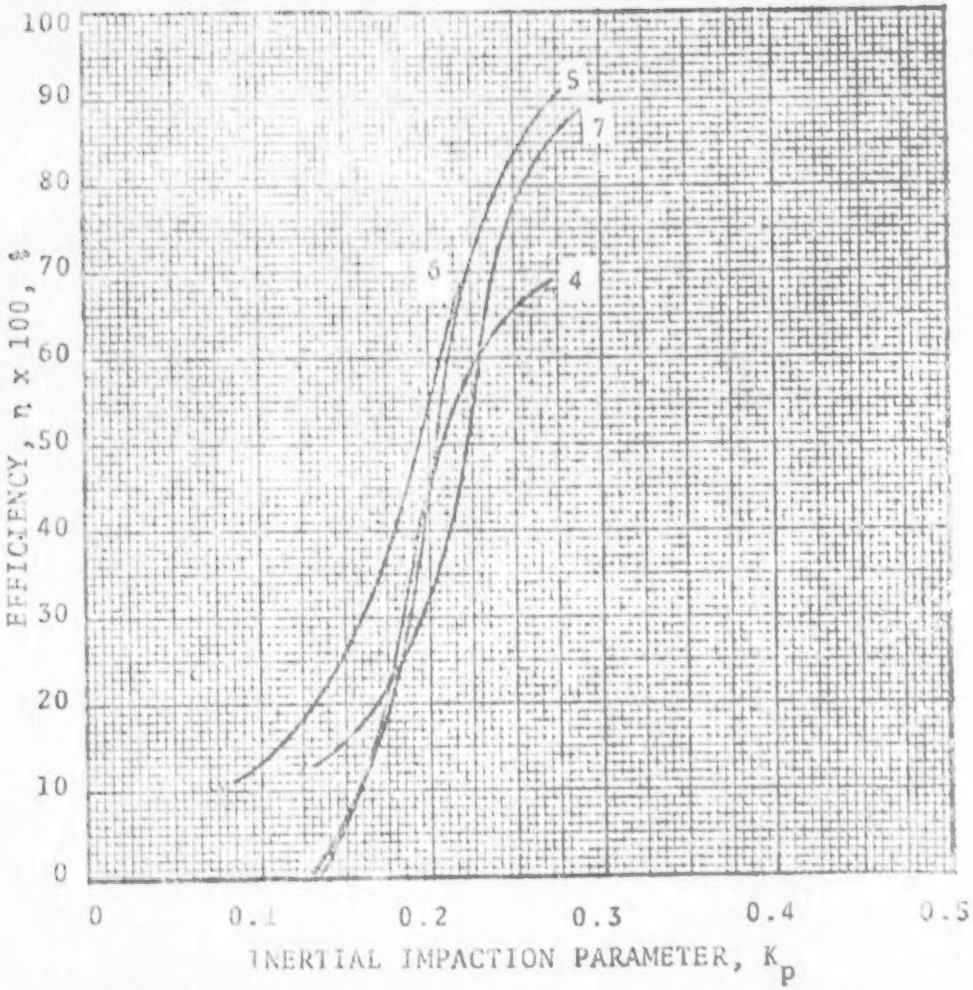

Figure B-9. Efficiency vs. inertial impaction parameter for A.P.T. M-1 cascade impactor, stages 4-7.

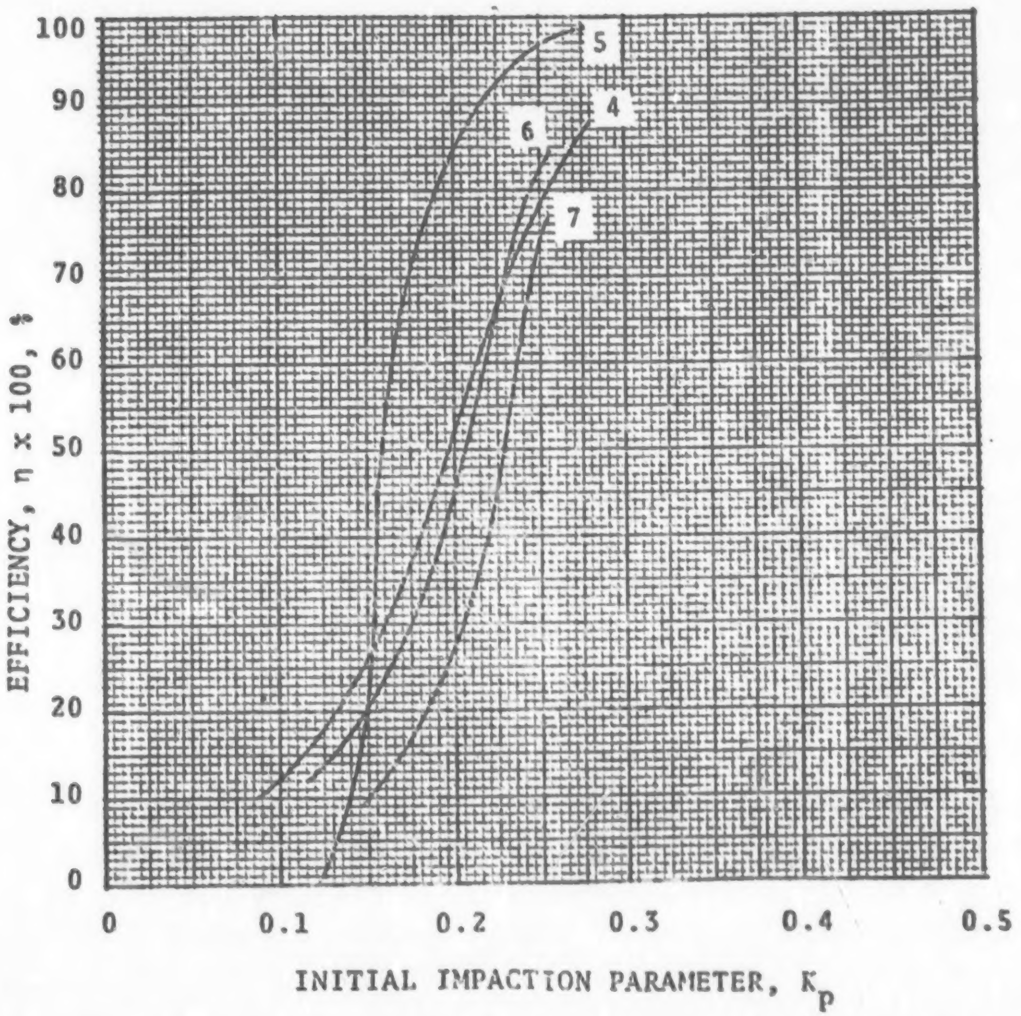

Figure B-10. Efficiency vs. inertial impaction parameter for Andersen non-viable cascade impactor, stages 4-7.

SECTION B-6

DISCUSSION

B-6.1 REPRODUCIBILITY

The data obtained with the procedure described above have been quite reproducible, as illustrated by Figure B-6. Generally the data for a single stage fall within a band width of inertial impactor parameter values ranging about 0.02 or 0.03. Thus, the scatter about a cut parameter is about ±8 percent. The corresponding scatter of cut diameter values would be ±4 percent. Similarly, a variation of ±10 percent in impaction parameter corresponds to a variation of about ±5 percent in particle cut diameter.

B-6.2 ACCURACY

One way to estimate the accuracy of the impactor calibration is to compare the results with published theory and experimental data. Figure B-11 is an efficiency plot which compares the averaged results for all four stages of each impactor with a few published experimental and theoretical results. It can be seen that the overall average cut parameters are within a spread of about 0.3 (signifying about 8 percent spread of cut diameters) for everything but the Ranz and Wong experimental data.

Curves "C" and "D" show the effect of jet length to diameter ratio, s/d_c, ranging from 3 for "C" to 10 for "D", from Mercer and Stafford's experimental data. The jet length/diameter ratios for the impactor stages whose calibrations are reported here are presented in Table B-3. It can be seen that the ratios range between 2.4 and 12.5, with the APT M-1 having the smallest variation.

Another factor whose effect is related to that of (s/d_c) is the shape of the orifice in the jet plate. Of the three impactors calibrated, only

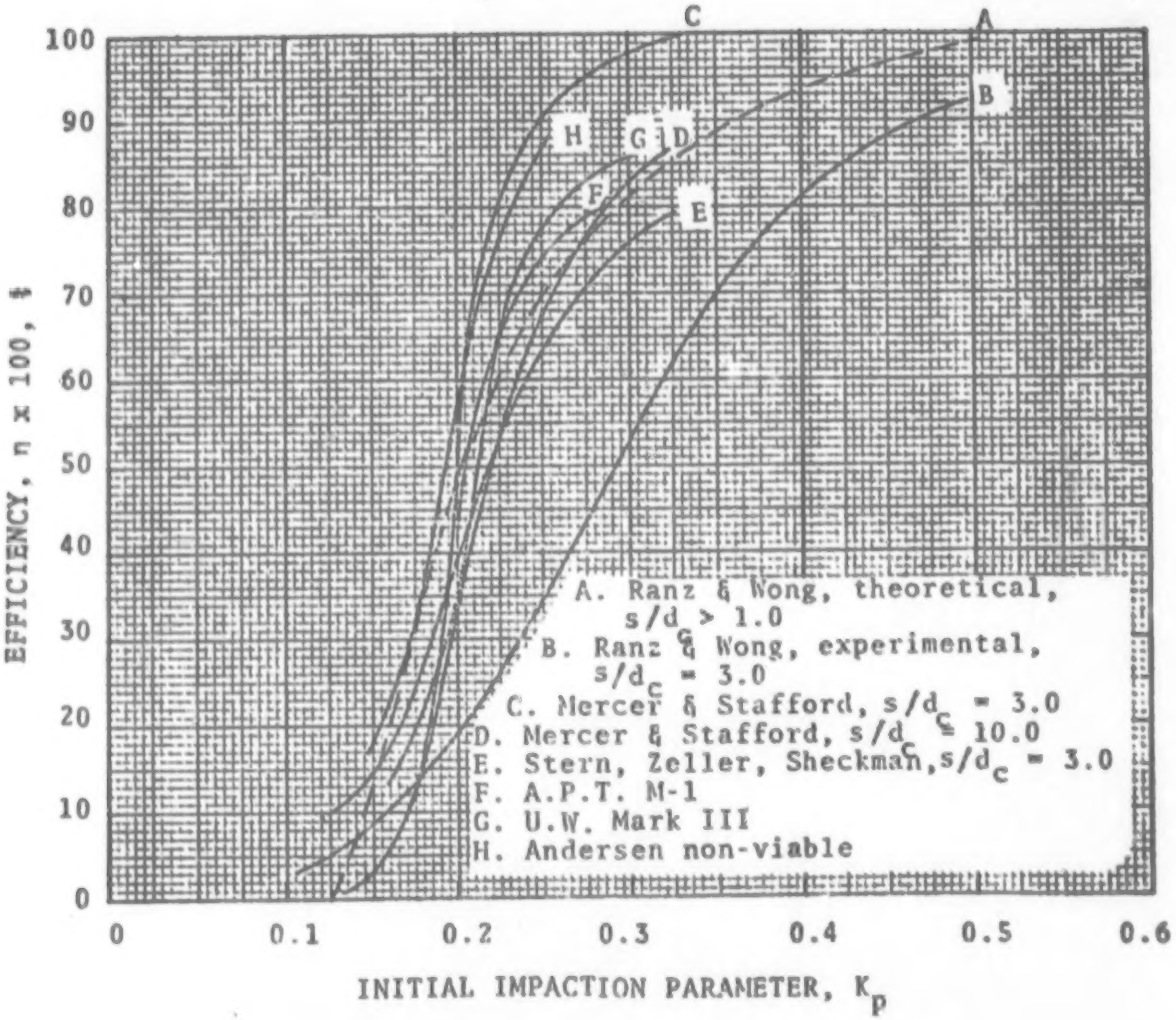

Figure B-11. Efficiency vs. inertial impaction parameter for comparison.

TABLE B-3. LENGTH/JET DIAMETER(s/d_c) FOR CASCADE IMPACTORS

	Stage - s/d_c			
Impactor	4	5	6	7
APT M-1	3.1	2.4	3.5	4.6
U.W. Mark III (New)	4.0	6.2	9.2	12.5
Andersen (non-viable)	4.7	7.3	9.8	9.8

the APT M-1 has converging orifices in the jet plates. For the impactors with cylindrical orifices the jet diameter and velocity depend on jet plate thickness as well as (s/d_c). While detailed discussion of impactor design and theory is beyond the scope of this report, it is important to note that such factors do influence the performance of the impactor and should be recognized when comparing experimental and theoretical results.

B-6.3 STAGE VARIATIONS

Turning back to Figures B-8, B-9, and B-10, it can be seen that the cut characteristics are generally "sharp" (i.e., efficiency rises steeply over a small impaction parameter range). However, the fourth stages for both the APT and the UW impactors show a pronounced decrease in curve slope above the cut point. This suggests that particle bounce may occur at higher velocities for these stages.

The variation of cut parameter values is least for the APT stages and greatest for the Andersen. This is believed to be due in part to the close control of (s/d_c) and the use of converging orifices in the APT M-1. It was also noted that some of the jet holes in the Andersen plates tested were not round, but roughly triangular. Such non-uniformity of the jet holes could be responsible for variations in cut parameter between impactor stages.

B-6.4 CONCLUSIONS

The procedure outlined in this report provides a simple technique by which inertial impaction devices may be calibrated. Such factors as loading, particle bounce, wall losses, electrostatic and condensation effects, which may occur during source testing, are evaluated by this technique to some degree. The calibration method, therefore, provides a reliable, intrinsic efficiency and is applicable to laboratory and field data obtained by careful C.I. operation.

SECTION B-7

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SECTION B-8

SAMPLE CALCULATIONS

B-8.1 AERODYNAMIC DIAMETER

PSL Diameter - 0.5 μm

Particle density, $\rho_p = 1.05\ \mathrm{g/cm^3}$

Cunningham slip correction factor corresponding to a diameter of 0.5 μm, is 1.33

$$D_{AI} = D\left(C\,\rho_p\right)^{1/2} = 0.5\ \left((1.33)(1.05)\right)^{1/2} = 0.59\ \mu mA$$

(The use of Figure B-4 yields a value of about 0.58 μmA)

B-8.2 GAS VELOCITY THROUGH JET

Number of jets, $X_j = 110$

Diameter of jet, $D_j = 0.0343$ cm

Sample flow rate at conditions of operation, $Q_s = 20$ /min

$$V_j = \frac{4Q_s}{X_j\ V_j} = \frac{4(20)(1000)}{(110)(\pi)(0.0343)^2(60)} = 3.28 \times 10^3\ \mathrm{cm/sec}$$

B-8.3 INERTIAL IMPACTION PARAMETER

Gas velocity at conditions of jet, $V_j = 3.28 \times 10^3$ cm/sec
Viscosity of Gas at conditions of jet, $\mu = 1.8 \times 10^{-4}$ poise
Jet diameter, $D_j = 0.0343$ cm
Aerodynamic diameter = 0.58 μmA

$$K_p = \frac{D_{AI}^2 V_j}{9 \mu D_j} = \frac{(0.58)^2(3.28 \times 10^3)(10^{-8})}{9(1.8 \times 10^{-4})(0.0343)} = 0.20$$

B-8.4 CONCENTRATION MEASUREMENT

Consider PSL particle diameter = 0.5 μm

Impactor Inlet

Concentration on 1.0 μm channel = 0.01×10^6 cm^{-3}
Concentration on 0.3 μm channel = 1.01×10^6 cm^{-3}
Net concentration measured = $(1.01 - 0.01) \times 10^6$ cm^{-3}
= 1.00×10^6 cm^{-3}
Concentration at 0.5 μm potentiometer setting = 1.00×10^6 cm^{-3}
Sample flow rate before dilution = 3.5 l/min
Sample flow rate after dilution = 7.0 l/min
Actual concentration entering impactor,

$$n_i = \frac{7.0 \text{ l/min}}{3.5 \text{ l/min}} (1.00 \times 10^6 \text{ cm}^{-3}) = 2.00 \times 10^6 \text{ cm}^{-3}$$

Impactor Outlet

Concentration on 1.0 μm channel = $0.001 \times 10^6\ \text{cm}^{-3}$

Concentration on 0.3 μm channel = $0.50 \times 10^6\ \text{cm}^{-3}$

Net concentration measured = $0.50 \times 10^6\ \text{cm}^{-3}$

Concentration at 0.5 μm potentiometer setting = $0.50 \times 10\ \text{cm}^{-3}$

Sample flow rate before dilution = 3.5 l/min

Sample flow rate after dilution = 7.0 l/min

Actual concentration exiting impactor,

$$n_o = \frac{7.0\ \text{l/min}}{3.5\ \text{l/min}} (0.50 \times 10^6\ \text{cm}^{-3}) = 1.00 \times 10^6\ \text{cm}^{-3}$$

B-8.5 EFFICIENCY AND PENETRATION

Inlet concentration, $n_i = 2 \times 10^6$ particles/cm^3

Outlet concentration, $n_o = 1 \times 10^6$ particles/cm^3

$$Pt = \frac{n_o}{n_i} = \frac{1 \times 10^6}{2 \times 10^6} = 0.5, \text{ fraction}$$

$$\eta = 1 - Pt = 0.5$$

Percent efficiency = 0.5 × 100 = 50 percent

B-8.6 CUT DIAMETER FOR A GIVEN STAGE

Inertial impaction parameter at 50 percent efficiency, $K_{p_{50}} = 0.20$

Jet gas velocity, $V_j = 3.28 \times 10^3$ cm/sec

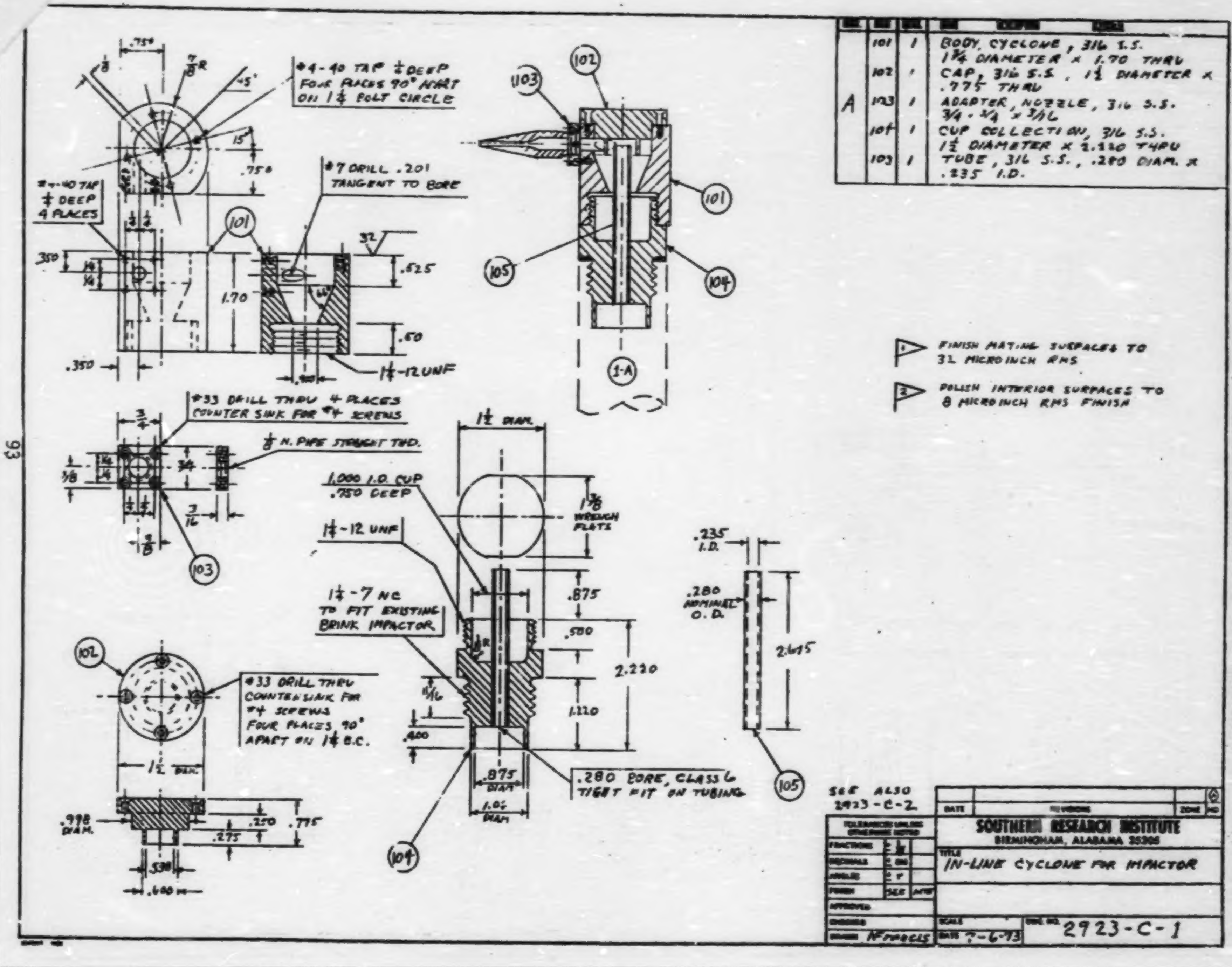
Viscosity of gas at conditions of jet, $\mu = 1.8 \times 10^{-4}$ poise

Jet diameter, $D_j = 0.0343$ cm

$$D_{AI,50} = \left(\frac{K_{p_{50}}\ 9\ \mu\ D_j}{V_j\ (10^{-8})}\right) = \left[\frac{(0.20)(9)(1.8 \times 10^{-4})(0.0343)}{(3.28 \times 10^3)\ (10^{-8})}\right] = 0.58\ \mu MA$$

APPENDIX C

DESIGN DRAWINGS, BRINK IN-LINE CYCLONE AND IMPACTOR


101 1 BODY, CYCLONE, 316 S.S. 1 3/4 DIAMETER x 1.70 THRU
102 1 CAP, 316 S.S., 1 1/2 DIAMETER x .775 THRU
A 103 1 ADAPTER, NOZZLE, 316 S.S. 3/4 - 3/4 x 3/16
104 1 CUP COLLECTION, 316 S.S. 1 1/2 DIAMETER x 2.220 THRU
105 1 TUBE, 316 S.S., .280 DIAM. x .235 I.D.
1 FINISH MATING SURFACES TO 32 MICROINCH RMS
2 POLISH INTERIOR SURFACES TO 8 MICROINCH RMS FINISH
#4-40 TAP 1/4 DEEP FOUR PLACES 90° APART ON 1 1/4 BOLT CIRCLE
#4-40 TAP 1/4 DEEP 4 PLACES
#7 DRILL .201 TANGENT TO BORE
1 1/4-12 UNF
#33 DRILL THRU 4 PLACES COUNTER SINK FOR #4 SCREWS
1/8 N. PIPE STRAIGHT THD.
1.000 I.D. CUP .750 DEEP
1 1/4-12 UNF
1 1/4-7 NC TO FIT EXISTING BRINK IMPACTOR
1 1/2 DIAM.
1 3/8 WRENCH FLATS
.280 BORE, CLASS 6 TIGHT FIT ON TUBING
#33 DRILL THRU COUNTERSINK FOR #4 SCREWS FOUR PLACES 90° APART ON 1 1/4 B.C.
.235 I.D.
.280 NOMINAL O.D.
2.615
.875
.500
2.220
1.220
.400
.875 DIAM
1.06 DIAM
.998 DIAM.
.250
.275
.775
.530
.600
.750
.525
.50
1.70
.350
1-A
101
102
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SOUTHERN RESEARCH INSTITUTE
BIRMINGHAM, ALABAMA 35205
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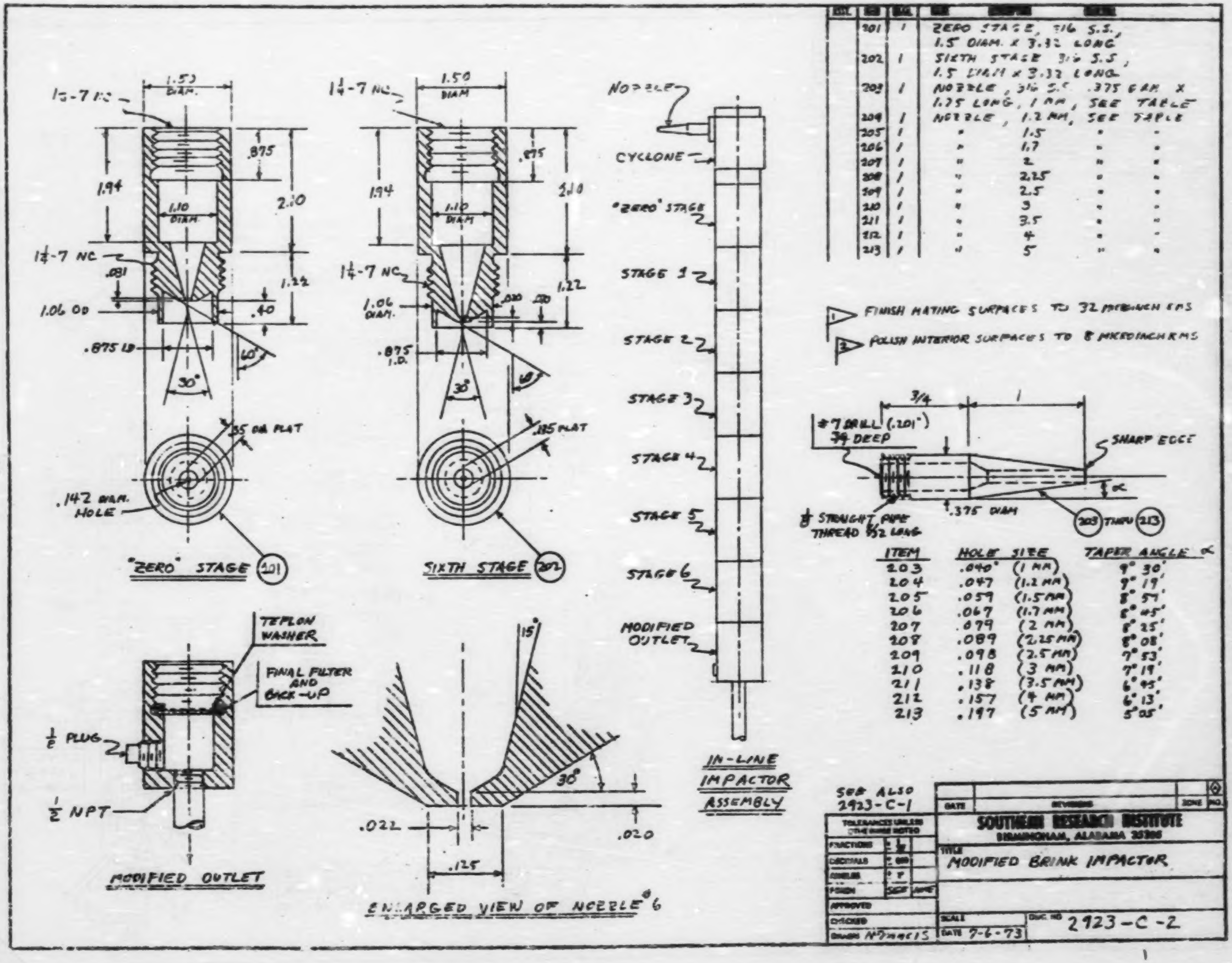

1½-7 NC
1.50 DIAM.
.875
1.94
2.10
1.10 DIAM
1¼-7 NC
.081
1.06 OD
.40
1.22
.875 I.D.
60°
30°
.35 DIA FLAT
.142 DIAM. HOLE
"ZERO" STAGE
201
1¼-7 NC
1.50 DIAM
.875
1.94
2.10
1.10 DIAM
1¼-7 NC
1.06 DIAM.
.020
.020
1.22
.875 I.D.
30°
60°
.115 FLAT
SIXTH STAGE
202
NOZZLE
CYCLONE
"ZERO" STAGE
STAGE 1
STAGE 2
STAGE 3
STAGE 4
STAGE 5
STAGE 6
MODIFIED OUTLET
IN-LINE IMPACTOR ASSEMBLY
TEFLON WASHER
FINAL FILTER AND BACK-UP
⅛ PLUG
½ NPT
MODIFIED OUTLET
15°
30°
.022
.125
.020
ENLARGED VIEW OF NOZZLE #6
3/4
1
#7 DRILL (.201") ¾ DEEP
SHARP EDGE
α
⅛ STRAIGHT PIPE THREAD 5/32 LONG
.375 DIAM
203 THRU 213

	201	1	ZERO STAGE, 316 S.S., 1.5 DIAM. x 3.32 LONG
	202	1	SIXTH STAGE 316 S.S, 1.5 DIAM x 3.32 LONG
	203	1	NOZZLE, 316 S.S .375 DIAM. X 1.75 LONG, 1 MM, SEE TABLE
	204	1	NOZZLE, 1.2 MM, SEE TABLE
	205	1	" 1.5 " "
	206	1	" 1.7 " "
	207	1	" 2 " "
	208	1	" 2.25 " "
	209	1	" 2.5 " "
	210	1	" 3 " "
	211	1	" 3.5 " "
	212	1	" 4 " "
	213	1	" 5 " "

1 FINISH MATING SURFACES TO 32 MICROINCH RMS

2 POLISH INTERIOR SURFACES TO 8 MICROINCH RMS

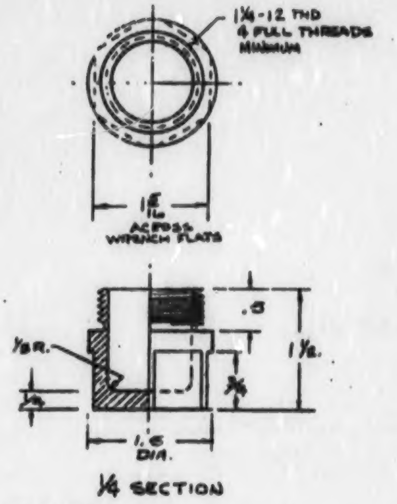
ITEM	HOLE SIZE		TAPER ANGLE α
203	.040"	(1 MM)	9° 30'
204	.047	(1.2 MM)	9° 19'
205	.059	(1.5 MM)	8° 57'
206	.067	(1.7 MM)	8° 45'
207	.079	(2 MM)	8° 25'
208	.089	(2.25 MM)	8° 08'
209	.098	(2.5 MM)	7° 53'
210	.118	(3 MM)	7° 19'
211	.138	(3.5 MM)	6° 45'
212	.157	(4 MM)	6° 13'
213	.197	(5 MM)	5° 05'

SEE ALSO
2923-C-1

SOUTHERN RESEARCH INSTITUTE
BIRMINGHAM, ALABAMA 35205

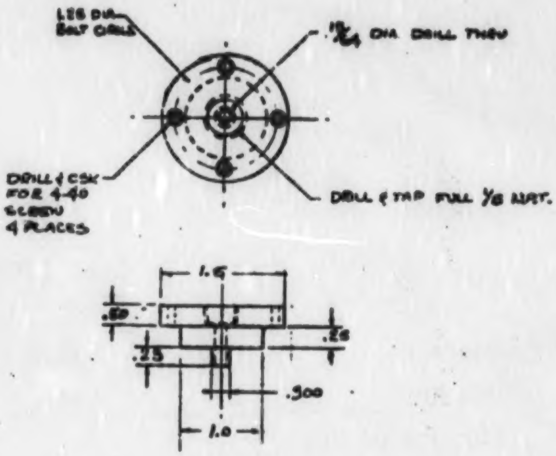
TITLE MODIFIED BRINK IMPACTOR

DRAWN McInnis
DATE 7-6-73
DWG. NO. 2923-C-2

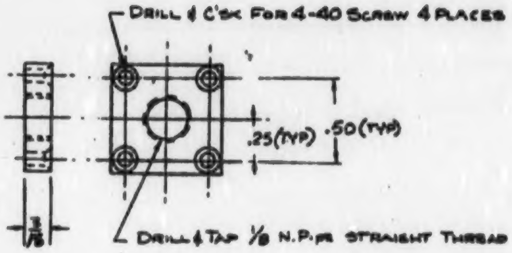

1¼-12 THD
4 FULL THREADS
MINIMUM
1 15/16
ACROSS
WRENCH FLATS
.5
1/8 R.
1½
3/4
1/4
1.6
DIA.
¼ SECTION

Notes
1. Mat'l - 316 Stnl. Steel
2. Polish Inside

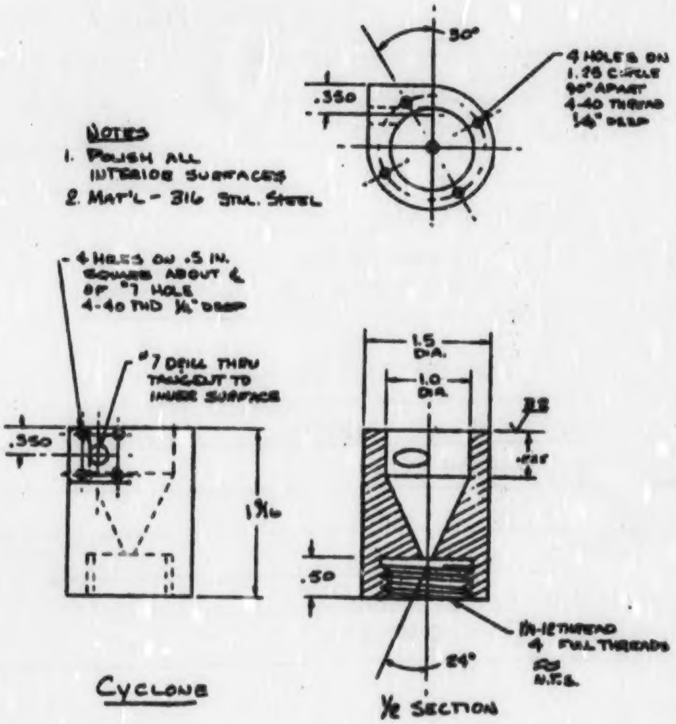
Collection Cup


1.25 DIA.
BOLT CIRCLE
19/64 DIA. DRILL THRU
DRILL & CSK
FOR 4-40
SCREW
4 PLACES
DRILL & TAP FULL ⅛ NPT.
1.6
.50
.25
.25
.300
1.0

VORTEX TUBE AND OUTLET


DRILL & C'SK FOR 4-40 SCREW 4 PLACES
.25(TYP)
.50(TYP)
3/8
DRILL & TAP ⅛ N.PIPE STRAIGHT THREAD

Nozzle Adaptor


30°
.350
4 HOLES ON
1.25 CIRCLE
90° APART
4-40 THREAD
1/4" DEEP
4 HOLES ON .5 IN.
SQUARE ABOUT ℄
OF #7 HOLE
4-40 THD 1/4" DEEP
#7 DRILL THRU
TANGENT TO
INNER SURFACE
.350
1 9/16
1.5
DIA.
1.0
DIA.
32
.625
.50
1¼-12 THREAD
4 FULL THREADS
AS
N.T.S.
24°
½ SECTION

Notes
1. Polish all interior surfaces
2. Mat'l - 316 Stnl. Steel

Cyclone

APPENDIX D

COST ESTIMATING DATA SHEET

Quote No. ______________ Client ______________________________
Job No. ______________ Date ______________ Location ______________
Purpose of Test ____
Type of Test -- Particulate __________________________________
Gases ______________________________________
Particulate Sizing ________________________________
Auxiliary Analysis ____
____

PERSONNEL	COST ESTIMATING--PROFESSIONAL SERVICES				
	Chemist/Engineers Meteorologist $________/Hr.		Project Director Superv. Engr. $________/Hr.		
	Hrs.	Cost	Hrs.	Cost	Total Cost
1.0 Pre-Survey					
1.1 Travel Time					
No. of Men					
2.0 Consulting					
3.0 Preparation of Test Protocol					
4.0 Construction Special Test Equip.					
5.0 Project Planning					
6.0 Field Test					
No. of Men					
7.0 Lab Analysis					
8.0 Calculations & Report Writing					

Appendix D (continued)
Page 2

PERSONNEL		COST ESTIMATING--PROFESSIONAL SERVICES				
		Chemist/Engineers Meteorologist $________/Hr.		Project Director Superv. Engr. $________/Hr.		
		Hrs.	Cost	Hrs.	Cost	Total Cost
9.0	Consulting & Design					
10.0						
11.0	Total					

Out-of-Pocket Cost
(see next page) ____________

TOTAL COST ____________

Appendix D (continued)
Page 3

Quote No. ____________ Client ______________________________

Job No. ________________ Date __________ Location __________

COST ESTIMATING OUT-OF-POCKET EXPENSES

1. Air Fare ______ Round Trips @ $ _______ × ____men ___________
   Air Fare ______ Round Trips @ $ _______ × ____men ___________
   Air Fare ______ Round Trips @ $ _______ × ____men ___________
2. Vehicle Rentals ___________________________ ___________
3. Shipping (Air Freight, Excess Baggage) ___________ ___________
4. Per Diem ______ men × $ _____/day × _______ days ___________
   Per Diem ______ men × $ _____/day × _______ days ___________
   Per Diem ______ men × $ _____/day × _______ days ___________
   Per Diem ______ men × $ _____/day × _______ days ___________
5. Limousine Service, Parking ___________________ ___________
6. Miscellaneous ___________________________ ___________
7. Computer Time ___________________________ ___________
8. Car Expenses ¢/mile × ____ miles ____ + tolls ___ ___________
9. Trailer Expenses ¢/mile ×____ miles_____ + tolls ___ ___________
10. Expendable Supplies ______________________ ___________
11. Special Equipment ________________________ ___________
12. General Supplies _________________________ No Charge

TOTAL: ___________

APPENDIX E

PRELIMINARY SURVEY FOR PARTICULATE SIZING

PLANT DATA Date: ______________________

Company Name: ______________________________________

Address: __________________ City: ____________ State: ________

Name of Contacts: ____________________ Title: ____________________

____________________ Title: ____________________

____________________ Title: ____________________

Telephone Number: ____________________

Process Description: __________________________________

____

____

(Operating Schedule): _________________________________

____

____

(Batch or Continuous): ________________________________

____

____

(Rates/Variability): __________________________________

____

____

AIR POLLUTION CONTROL EQUIPMENT

Description: ____

____

(Operating Schedule): _________________________________

____

(Rate/Variability): ___________________________________

____

Appendix E (continued)
Page 2
Preliminary Survey for Particulate Sizing

Sketch of Sampling Sites (with approximate dimensions, ports located, upstream and downstream equipment if important).

Appendix E (continued)
Page 3
Preliminary Survey for Particulate Sizing

CONDITIONS AT SAMPLING SITES

Pressure

Temperature

Gas Rate

Gas Composition

Particulate Loading

Pre-cutter Required?

Approx. Size Dist.

Weight Gain/Loss by Substrates, Filter

Weight Gain/Loss by Grease

Particulate Condition--hard, sticky, etc.

Wet or Dry

Port Size/Fitting Type

Condensation?

Notes

Appendix E (continued)
Page 4
Preliminary Survey for Particulate Sizing

1) Electricity Source
   a. Amperage per circuit ______________________________
   b. Location of fuse box ______________________________
   c. Extension cord lengths __________________ Quantity ______
   d. Adapters Needed ______________________________
   e. Electrician ______________________________

2) Safety Equipment Needed
   a. Hard hats __________
   b. Safety glasses __________
   c. Goggles __________
   d. Safety shoes __________
   e. Alarms __________
   f. Other __________

3) Ice
   a. Vendor ______________________________
   b. Location ______________________________

4) Solvents
   a. Vendor ______________________________
   b. Location ______________________________

5) Sampling Ports
   a. Who will provide ______________ Welder: ______________
   b. Size opening ______________________________

6) Scaffolding
   a. Height ______________________________
   b. Length ______________________________
   c. Vendor ______________________________
      Address ______________________________
      Telephone ______________________________

7) Distilled Water
   a. Vendor ______________________________
   b. Location ______________________________

8) Test Site Facilities
   a. Parking ________________
   b. Restroom ________________
   c. Laboratory Facilities ________________
   d. Clean-up Area ________________

9) Motels:
   a. ________________ Phone ________ Rate ________
   b. ________________ Phone ________ Rate ________
   c. ________________ Phone ________ Rate ________

10) Restaurants:
   a. New Plant ________________
   ____
   b. Near Motel ________________
   ____

11) Airport Convenient to Plant ________________ Distance ________

12) Comments: ________________
____
____
____
____
____
____
____

Survey By: ________________

APPENDIX F

SAFETY CHECKLIST

Date ____________________

Company ____________________

Location ____________________

A. MEDICAL:

1) Plant first aid available (yes/no) ________.
If available give location of unit and telephone number
____

2) Phone number for ambulance ____________________

3) Phone number for hospital ____________________

4) Comments: ____________________
____

B. TEST SITE CHECKLIST: Check if OK.

1) Ladders:
General conditions ______, rest stops ______, cage ______
Comments: ____________________
____

2) Scaffolds/Platforms:
General conditions ________, guardrails ________
toeboards ________, screening ________
Comments: ____________________
____

C. PERSONNEL PROTECTION EQUIPMENT: Check if needed.

1) Safety glasses ________, side shields ________
face shields ________, goggles ________, hard hat ________,
safety shoes ________ electrical hazard shoes ______,
life belt and safety block ________,
hearing protective devices _____, ladder climbing devices ___

2) Respiratory equipment:
Air purifying ________, air supplied ________,
self-contained ________,
Other ____________________
____

3) Body protection:
Chemical protective garments ____________
Heat protective garments ________________
Chemical gloves _________________________
Heat resistant gloves ___________________
Other ____

____

D. ARE FIRE EXTINGUISHERS AVAILABLE AT SITE _______________?

E. SPECIAL OR UNUSUAL TEST PROCEDURES AND SAFETY PRECAUTIONS NECESSARY:

____

____

____

____

____

APPENDIX G

SAMPLE CALCULATION

This sample calculation is based on data taken with a Brink impactor. The impactor was run in a wind tunnel with redispersed fly ash in an essentially ambient air stream. No SO_2 was present. The data are presented in Table G-1.

As stated in the section on reporting, it is necessary to determine and report cumulative distributions based on D_A, D_s, and D_{AI}. The calculation based on D_s will be presented in this appendix, with comments on D_A and D_{AI} when appropriate. Stage 3 will be completely worked through.

STEP 1: CALCULATE THE PRESSURE ON STAGE 3

The fraction of the pressure drop which occurs by stage 3 of the impactor must be measured for a given impactor. Usually most of the drop is across the last stage or so. For the Brink impactor, it has been determined that only 1.4 percent of the total impactor pressure drop occurs ahead of stage 3. The total pressure drop across the impactor was measured at 17.8 mm Hg.

$$P_j = P_s - f_{DP}(\Delta P_I) \qquad \text{(G-1)}$$

where:

f_{DP} = fraction of ΔP_I occurring ahead of stage [0.014]

ΔP_I = total pressure drop across the impactor, mm Hg [17.8 mm Hg]

P_s = stack pressure, mm Hg [764.8 mm Hg]

$$P_j = 764.8 \text{ mm Hg} - 0.014 \text{ (17.8 mm Hg)}$$

$$P_j = 764.6 \text{ mm Hg at stage 3.}$$

STEP 2: CALCULATE THE GAS MEAN FREE PATH AT STAGE 3 CONDITIONS

The equation for mean free path presented below is based on the Chapman-Enskog equation.

$$\ell = 8.572 \frac{\mu}{P_j} \left(\frac{T_j}{MW} \right) \qquad \text{(G-2)}$$

where:

T_j = temperature at stage, °K [300°K]
MW = molecular weight of gas stream [29 $\frac{g}{\text{g-mole}}$]
P_j = pressure on stage, mm Hg [764.8 mm Hg]
μ = viscosity at stage, poise [1.82×10^{-4} poise]
ℓ = mean free path, cm

$$\ell = 6.6 \times 10^{-6} \text{ cm}$$

STEP 3: ITERATIVE SOLUTION OF EQUATION (G-3) AND EQUATION (G-4)

$$D_{s,50} = \left(\frac{2.05\ \mu\ D_j^3\ P_j x_j}{C\ \rho_p\ Q_s\ P_s} \right)^{1/2} \qquad \text{(G-3)}$$

Where: $D_{s,50}$ = Stokes diameter cut-point of stage, cm
D_j = jet diameter on stage, cm [0.1396 cm]
x_j = number of jets on stage [1]
ρ_p = density of particles, g/cm³ [2.5 g/cm³]
Q_s = volumetric flow rate through impactor at stack conditions, cm³/sec [20.3 cm³/sec]

$$D_{s,50} = 1.4 \times 10^{-4} \left(\frac{1}{C} \right)^{1/2} \text{ cm}$$

$$C = 1 + \frac{2\ell}{D_{s,50}} \left((1.23 + 0.41 \exp \frac{-0.44\ D_{s,50}}{\ell}) \right) \qquad \text{(G-4)}$$

where:

C = Cunningham Correction Factor, dimensionless.

$$C = 1 + \frac{1.32 \times 10^{-5}}{D_{s,50}} \left((1.23 + 0.41 \exp (-6.67 \times 10^{4}\ D_{s,50}) \right)$$

For $D_{s,50}$ in the range of 1 μm (10^{-4} cm), the exponential term is <0.001 and can be neglected.

$$C = 1 + \frac{1.62 \times 10^{-5}}{D_{s,\ 50}}$$

From experience, choose $D_{s,50} = 1.5 \times 10^{-4}$ cm for the initial trial:

Trial 1: $D_{s,50} = 1.5 \times 10^{-4}$cm

$$C_1 = 1.108 \therefore D_{s,50}\big|_1 = 1.33 \times 10^{-4} \text{ cm}$$

First trial $D_{s,50}$ was too high.

Trial 2: $D_{s,50} = 1.2 \times 10^{-4}$ cm

$$C_2 = 1.134 \therefore D_{s,50}|_2 = 1.31 \times 10^{-4} \text{ cm}$$

Second trial was too low.

Trial 3: $D_{s,50} = 1.32 \times 10^{-4}$ cm

$C_3 = 1.122 \quad D_{s,50}|_3 = 1.32 \times 10^{-4}$ cm

AGREEMENT: $D_{s,50}$ on stage 3 = 1.32×10^{-4}cm = 1.32 μm

This series of calculations must be repeated for each stage of the impactor. The results are presented in Table G-1.

STEP 4: CALCULATION OF $D_{A,50}$ FOR IMPACTOR

$D_{A,50}$ is calculated in the same way $D_{s,50}$ was, except that the density is taken as 1.0 g/cm³.

STEP 5: CALCULATION OF $D_{AI,50}$ FOR IMPACTOR

In theory, $D_{AI,50}$ is calculated in the same way as is $D_{s,50}$, except that the density is taken as 1.0 g/cm³ and the Cunningham Correction Factor is set at 1.0. It can also be calculated as:

$$D_{AI,50} = D_{s,50} (\rho_p C)^{1/2} \tag{G-5}$$

STEP 6: CALCULATE THE STANDARD VOLUME OF THE SAMPLE*

The known flow rate, Q_s, is volumetric flow rate at stack conditions. It must be converted to standard conditions of 273°K and 760 mm Hg.

---

*This step is not necessary for a cumulative distribution, but will be illustrated. In steps 7 and 8, the mass actually caught on the stage, M_i, could be used rather than the ΔC_i which is illustrated. The ΔC_i term is usually used in place of mass for differential distributions. The calculation is valid as shown.

$$V_N = Q_s \, (1 - F_{H_2O}) \, \frac{P_s}{760} \, \frac{273}{T_s} \, \theta \qquad \text{(G-6)}$$

where:

V_N = impactor sample volume at standard conditions, Ncm^3
Q_s = sample rate at stack conditions, cm^3/sec [20.3 cm^3/sec]
F_{H_2O} = volume fraction of water in gas [0.019]
θ = sample time, sec [1800 sec]

$V_N = 3.28 \times 10^4 Ncm^3 = 0.0328 Nm^3$

STEP 7: CALCULATE THE CONCENTRATION OF PARTICULATE ON A STAGE

$$\Delta C_n = \frac{\Delta M_i}{V_N} (0.001) \qquad \text{(G-7)}$$

where:

ΔC_n = concentration of particulate which impacted on the stage, g/Nm^3
ΔM_n = mass of particles caught on the stage, mg [0.576 mg]

$\Delta C_3 = 0.0175 \ g/Nm^3$ on stage 3.

STEP 8: CALCULATION OF CUMULATIVE CONCENTRATION FRACTION SMALLER THAN STAGE D_{50}

$$\text{Weight percent smaller than } (D_{50})_k = \frac{\sum_{i=o}^{k} \Delta C_i}{\sum_{i=0}^{K} \Delta C_i} \times 100\% \qquad \text{(G-8)}$$

where:

i = o corresponds to the filter
i = k corresponds to the stage under study
i = K corresponds to the coarsest jet or cyclone.

Note that the stages are numbered differently for use in this equation than they have been previously; one must count from the bottom up. However the numbering is done, the mass percent caught on the final filter is the mass percent smaller than the D_{50} of the smallest stage. The sum of the mass percents caught on the smallest stage and on the final filter is the cumulative mass percent smaller than the D_{50} of the next to smallest stage, and so on up the impactor.

$$\begin{array}{l}\text{Weight percent smaller} = \dfrac{0.0085+0.0002+0.0017+0.0090\ \ 0.0175}{1.86144} \times 100\% \\ \text{than } D_{50} \text{ of Stage 3}\end{array}$$

Percent less than D_{50} of stage 3, 1.32 µm = 1.98%

STEP 9: PLOT DATA ON CUMULATIVE MASS PLOT

Percent less than stage $D_{s,50}$ versus $D_{s,50}$.

STEP 10: CALCULATE THE CUMULATIVE DISTRIBUTIONS FOR $D_{A,50}$ AND FOR $D_{AI,50}$ AND PLOT

TABLE G-1. DATA FROM BRINK IMPACTOR RUN

Stage	M, mg	ΔC_n g/Nm^3	% Smaller than specified size	$D_{s,50}$, µm
Arbitrary Maximum	--	--	100%	100
Cyclone	47.840	1.454	21.89%	9.39
0	6.336	0.193	11.52%	5.73
1	3.848	0.117	5.23%	3.25
2	1.992	0.0605	1.98%	1.93
3	0.576	0.0175	1.04%	1.32
4	0.296	0.0090	0.56%	0.71
5	0.056	0.0017	0.47%	0.46
6	0.008	0.00024	0.45%	0.28
Filter	0.280	0.0085		--
Totals	--	1.86144	--	--

Other Data: ΔP_i = 17.8 mm Hg
P_s = 764.8 mm Hg
f_{DP} for stage 3 = 0.014
μ = 0.000182 poise
MW of air = 29 g/g-mole
T_j = 300°K
D_j = 3rd stage jet diameter = 0.1396 cm
x_j = 1 jet per stage
ρ_p = particle density = 2.5 g/cm^3
Q = sample data at stack conditions = 20.3 cm^3/sec
R_s = stack temperature = 300°K
F_{H_2O} = volume fraction water in gas = 0.019
θ = sample time = 1800 sec

APPENDIX H

METRIC SYSTEM CONVERSION FACTORS

Non-metric	Multiplied by	Yields Metric
acfm	28.317	liters/min
°F	5/9 (°F-32)	°C
in.	2.54	cm
gr/acf	0.0023	g/liter
ft	30.48	cm
gr/acf	2.3	mg/liter